Cranfield University – Silsoe Campus

National Soil Resources Institute

This thesis was submitted for award of PhD.

Academic year: 2001-2002

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DESIGN OF A NOVEL PUNCH PLANTER CAPABLE OF PRODUCING EQUIDISTANT SEED SPACING OF IRREGULAR SHAPED SEEDS

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September, 2002

THIS THESIS IS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR DEGREE OF DOCTOR OF PHILOSOPHY – PhD

Cranfield University – National Soil Resources Institute

Ricardo Capúcio de Resende, PhD/2002

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Abstract

Plants uniformly spaced in the field have a more efficient use of resources, due to their even distribution. There are also a better ability to compete against weeds, less spread of disease and lodging. Consequently the yield should be improved. Precise seed placement and seed location in the field are important for the management of the crop at a plant-scale level, for such operations as mechanical weeding or herbicides applications.

A novel concept of a precision drill was developed to achieve an advanced control of seed placement and location in the soil. The fundamental principle adopted, was to trap seeds inside holes in the soil, to eliminate seed bounce and roll in the furrow. The concept is simple and consists of only three moving parts, two punch wheels and a fan, to precisely place the seeds in the soil. A rotary punch planter prototype was designed and built, including a vacuum operated seed metering unit and an air delivery system.

The prototype was tested under laboratory conditions to determine its performance in relation to seed placement, when planting wheat and pelleted sugar beet seeds. The experiments were done in a soil bin at 4, 6 and 8 km/h. Seed spacing and depth were set to 18 cm and 3 cm, respectively.

The results show that, once a seed had been successfully selected the prototype had the ability to precisely place seeds in the soil for wheat and sugar beet seeds, at all speeds tested. The grand mean for precision was 12.2%. The CP3 value for wheat and sugar beet at 8 km/h were 26.2 % and 60.8 %, respectively. The main problems encountered were seed selection at higher speeds, and incorrect seed transfers from the seed metering unit to the delivery punches, which occurred for both seeds at all speeds. The concept has proved to be effective and modifications of the seed metering mechanism to improve its performance is recommended to further improve upon the concept.

Acknowledgements

This work is dedicated to my wife Luciana.

I would like to thanks the Brazilian government that sponsored me through its agency CNPq (Conselho Nacional de Desenvolvimento Cientifico e Tecnológico).

I also wish to thank my employer, UFV (Universidade Federal de Viçosa), for the training opportunity given.

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1. Introduction, Aim and Objectives

1.1. Introduction

Uniform plant distribution in the field is important for the crop in a number of ways. Yield can be increased when equidistant plant spacing is achieved because the use of water, nutrients and light is optimised. A crop that is uniformly spread in the field develops better, becoming a stronger competitor in the fight against weeds. Uniform plant spacing also reduces lodging because of better root anchorage, and decreases the spread of diseases through reduced plant contact. All these benefits make accurate seed positioning in the soil paramount.

Precision agriculture is a new technology that manages temporal and spatial variability within a field to increase efficiency, improve quality and reduce the environmental impact of agriculture. There has been significant progress in precision agriculture technology in the last decade and farmers have been provided with an expanding suite of tools to measure and manage the variability throughout a field. The management of variability within a field is reaching the plant-scale level for some activities, requiring precise plant distribution to facilitate plant location.

The use of precision agriculture technology for mechanical weeding and herbicide applications requires treating a field at a very fine scale in order to reduce or eliminate the use of herbicides. A plant-scale approach has been used because it is necessary to precisely distinguish between the crop and weeds. Once this distinction is made weeds must be removed through mechanical weeding or precise herbicide applications. A uniform pattern of plant distribution and plant location in the field are crucial to perform these operations without disturbing the crop. Remote sensing and machine vision systems can easily make the distinction between plants and soil but there are difficulties with differentiating between crop and weeds.

Drilling is an early activity during crop production that establishes plant distribution in the field. Consequently, it has a strong influence not only on crop development but also on the precision of subsequent activities like mechanical weeding and herbicide applications. To date, the development of precision agriculture technology for drilling has concentrated on variable seed rate application. Controlling the pattern of seed placement over an area to produce an equidistant seed spacing in all directions and the measurement of seed location in the field are other avenues that can be explored to boost the strength of this technology.

Precision drills that open a furrow in the soil are affected by seed bounce and roll in the furrow that cause dispersion around the target position. The result is an uneven seed distribution within the row because the path followed by the seeds is not the same for all seeds drilled. This random component of seed placement makes the task of producing equidistant seed spacing in all directions and seed location in the field very difficult if not impossible.

The concept of punch planting eliminates seed bounce and roll because seeds are delivered and trapped inside holes in the ground instead of furrows. In this manner seed paths from the hopper to specific points in the soil are predictable and can be well controlled. Precise seed positioning in the soil can be achieved not only within the row but between rows in a synchronized way. Consequently, punch planting has an inherent advantage for uniform seed spacing in all directions and measurements of seed positions in the field compared with furrow planting.

To create a map of seed positions in the field it is necessary to combine the measurement of machine location in the field with seed placement across the width of the machine. Machine location can be precisely accomplished using the latest generation of GPS. Receivers using real time kinematics have a standard deviation from the mean of approximately one centimetre. Seed location may be solved through the development of a precision punch planter.

Seed maps could be used to monitor the performance of the drill itself. It can help to explain yield variability. Activities like herbicide applications and mechanical weeding can be enhanced with the use of seed maps mainly when combined with machine vision to reconstruct plant position in the field. This technology could then be used to manage each plant individually.

Yield maps, soil maps, weed maps, disease maps, pest maps and remote sensing images are some examples of recorded variability in a field. Based on this information application rates of inputs like seeds, fertilizer, herbicides and pesticides are prescribed according to agronomic requirements at each specific location in the field. The application of these inputs is then varied throughout the field to optimise crop production.

1.2. Aim

The overall aim of this research was to develop precision drilling technology for precision agriculture.

1.3. Objectives

The main objectives of this research were:

- to review literature related to precision drilling and precision agriculture;
- to design and build a precision punch planter prototype for cereals;
- to evaluate the punch planter prototype's ability to precisely place seeds in the soil;
- to measure seed locations while drilling in the field, to build a seed location map for precision agriculture.

2. Research methodology

The research methodology consisted of two main phases: the creation of a solution and the evaluation of its performance. During the first phase a new conceptual embodiment of a precision punch planter was developed and a prototype was constructed. In the second stage this prototype was evaluated to test its ability to produce equidistant seed spacing and uniform seed depth. The research methodology was divided into a design methodology, prototype manufacture, test apparatus and instrumentation manufacture and assembly, and an evaluation methodology.

2.1. Design Methodology

The design methodology adopted for this research is a systematic approach to engineering design that was proposed by Pahl and Beitz (1996).

The design activity was split into four main phases:

- Clarifying the task: specification of information
- Conceptual design: specification of principle
- Embodiment design: specification of layout (construction)
- Detailed design: specification of production

After the design phase a precision punch planter prototype was manufactured and assembled.

Figure 2.1. shows a diagram with the main design activities and the flow of information among them. According to Pahl and Beitz (1996) the crucial activities during the design process in chronological order are: the optimisation of the principle, the optimisation of the layout, shape and materials, and the optimisation of the production. Note that these activities overlap to a considerable extent, therefore there is no clear border between the design phases.

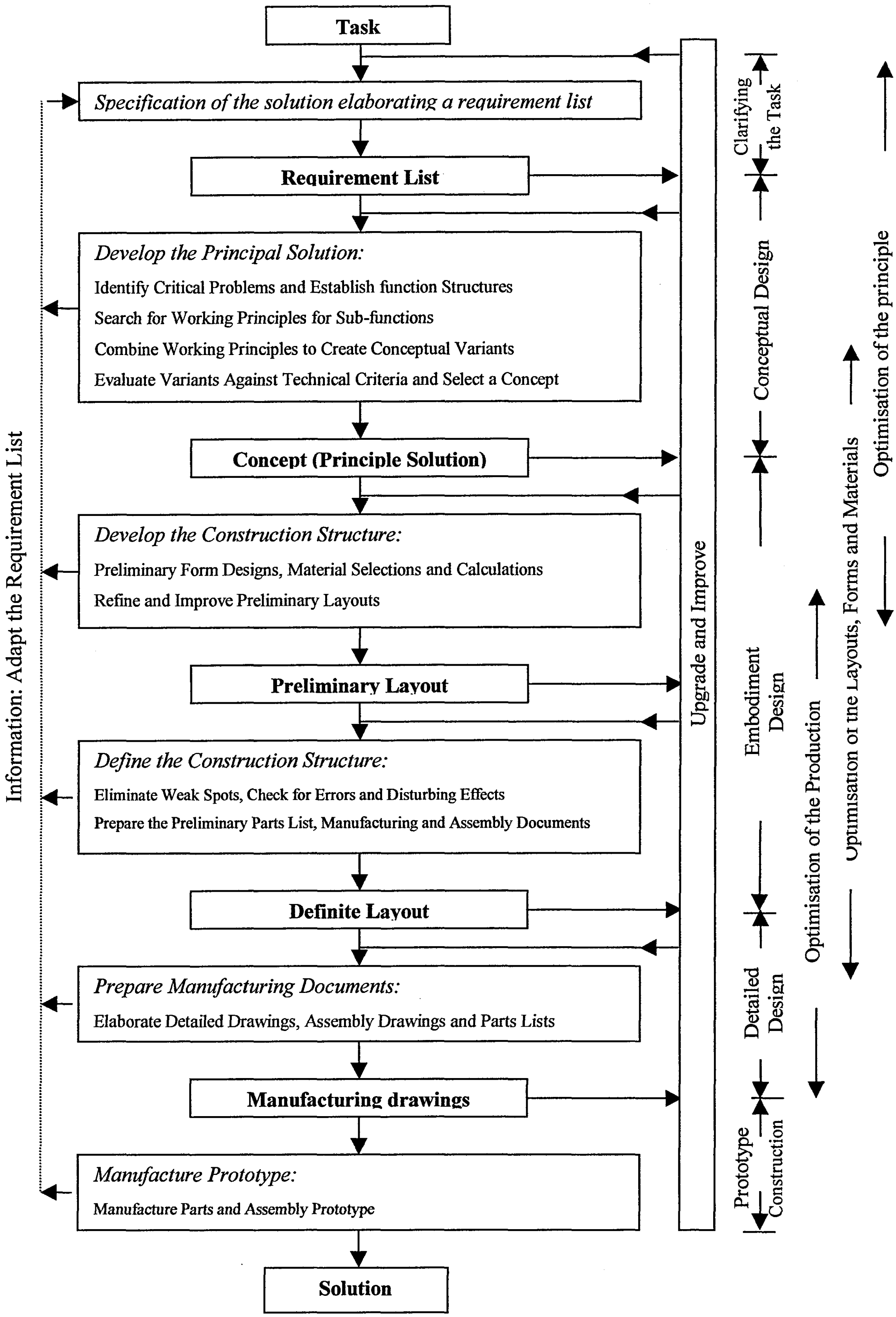


Figure 2.1. Main design phases - Adapted from Pahl and Beitz (1996)

2.1.1. Clarifying the task

The design activity started by clarifying the task of accurately placing and locating seeds in the soil. During this phase information was collected about the requirements and constraints that the precision planter had to fulfill and overcome. This information was arranged in a requirement list. Subsequent phases were based on this document. The requirement list was continuously updated as the design progressed

2.1.2. Conceptual Design

The conceptual design phase established the principle of the solution. It started with the abstraction of the essential problems of precisely placing seeds in the soil. Following, a structure of functions necessary to achieve precise seed placement was established. At this point the solution to each function was not considered. Each function was indicated by a verb and a noun, for example "select seed, open hole, deliver seed and close hole". The next step was the search for suitable working principles for all these functions. Solutions found during the literature review were considered and more solutions were developed. These solution principles were organised in a morphological matrix. Several solution variants were built combining those principles into working structures. These solution variants were then evaluated against technical criteria. The best solution concept was selected to be developed during the next phase, the embodiment design.

2.1.3. Embodiment Design

During this phase the conceptual solution was used to develop the overall layout of the machine. The same strategy of developing multiple solutions for the same problem was used here. Several preliminary layouts were produced to explore different construction structures. Advantages and disadvantages of each solution became clearer as the design progressed. The most promising layout was selected and improved incorporating ideas and solutions from others and eliminating weak spots. Usually it was necessary to make several changes to optimise the final layout making this phase extremely laborious. The construction of models were very valuable during this phase. The resulting deliverable from this phase was the specification of the layout of the precision punch planter prototype.

2.1.4. Detailed Design

Manufacturing gained more importance as the embodiment process progressed. During the detail design, the arrangement, the shape and the dimensions of all individual parts were finally established. Frequent changes to the shape and material of components were necessary to optimise manufacture. Attention to detail was crucial during this stage. The resulting deliverable from the detail design phase was the production drawings, which were completed using Autodesk - AutoCAD R13 software.

2.2. Prototype manufacture

One planter unit of the precision punch planter prototype was manufactured and assembled at the workshop of Cranfield University – Silsoe. Conventional methods of manufacture were used.

2.3. Test apparatus and instrumentation system

An electric propulsion system was developed and manufactured to pull the machine along the soil bin. A wire rope loop was built using a driving pulley and a tension pulley as supports. The wire rope had three turns around the driving pulley to provide extra friction to drive the rope. This winch was instrumented to measure and display distance and speed. An operator controlled the speed via a control box.

2.4. Prototype evaluation methodology

The prototype was evaluated in a soil bin to test its ability to precisely place seeds in the soil. Seed depth and position were measured. The performance of the prototype was evaluated for two types of seeds (wheat and pelleted sugar beet) and three travel speeds (4, 6 and 8 km/h). The prototype was set up to produce a seed spacing of 18 cm and a seed depth of 3 cm.

2.4.1. Seed type – wheat and pelleted sugar beet

The prototype's performance was evaluated for wheat and pelleted sugar beet seeds. Two seed types were chosen to evaluate the performance of the prototype with both regular and irregular shaped seeds. Wheat seeds are irregular in shape and size therefore they are much more difficult to be selected than pelleted sugar beet seeds, which are ball shaped and uniform in size.

2.4.2. Travel speed

Three forward velocities of 4, 6 and 8 km/h were used to test the influence of speed on its performance.

2.4.3. Measures of accuracy

Eight measures of accuracy based on seed depth and seed position measurements were used to evaluate the performance of the punch planter. They were: the multiple index – D, the quality of feed index – A, the missing index – M, precision – C, the coefficient of precision – CP3, the mean seed spacing, the mean seed spacing within the target range and the mean seed depth. Seed spacing histograms were also used to provide a graphical illustration.

The first four measures of accuracy were defined by the International Organization for Standardization. They are all based on the theoretical seed spacing. Kachman et al. (1995) evaluated several measures of accuracy for precision drills and concluded that these four measures (D, A, M and C) are better than the mean and standard deviation combined to describe the planter's ability to produce uniform seed spacing. These measures are based on the frequency of seed spacing of five distinct regions found in the seed spacing histograms. The five regions are, region 1 [0 to $0.5X_{ref}$], region 2 ($0.5X_{ref}$ to $1.5X_{ref}$], region 3 ($1.5X_{ref}$ to $2.5X_{ref}$], region 4 ($2.5X_{ref}$ to $3.5X_{ref}$] and region 5 ($3.5X_{ref}$, ∞), where X_{ref} represents the target seed spacing.

The multiple index (D) is the percentage of seed spacing that are less than or equal to 0.5 times the theoretical seed spacing (region1). This index was used as an indicator of the frequency of double seed selections.

The quality of feed index (A) is the percentage of seed spacing that are close to the target spacing (inside region 2). This index was used as an indicator of the frequency of single seed selections.

The missing index (M) is the percentage of seed spacing that are greater than 1.5 times the theoretical seed spacing (regions 3, 4 and 5). This index was used as an indicator of the frequency of missing seeds.

Precision (C) is a measure of variability in spacing between seeds around the target spacing. It is the sample standard deviation (of the seed spacing within the range of 0.5 to 1.5 times the theoretical spacing) divided by the theoretical seed spacing. Precision (C) is similar to the coefficient of variation of the seed spacing that are classified as singles. It differs from the usual coefficient of variation in that it uses the theoretical seed spacing as the denominator in place of the sample mean. The precision (C) is not affected by the outliers because its calculation does not take into account any seed spacing outside the target range. Multiple and missing seeds are removed. It will only measure the degradation of performance within the target range. The maximum theoretical value for precision is 50%. This occurs when half of the seed spacing are at the lower limit and half at the upper limit of the target range. This would indicate that the theoretical spacing was incorrectly specified. A precision of 29% would indicate that all seed spacing are uniformly spread within this range. The smaller this coefficient, the more precise is the drill. This index was used as an indicator of the accuracy on seed placement in the soil.

The coefficient of precision (CP3) was used as another measure of accuracy of seed placement in the soil. It is the percentage of seed spacing that occurred within a 3 cm range centred on the mode spacing. According to Panning et al. (1997) this parameter was proposed by Smith et al. (1991) and adopted by researchers at L'Institut Technique Francais de la Betterave Industrielle (1994). Its popularity has been growing since because it is a very good way to represent the ability of a planter to space seeds near the true planter spacing setting.

Other measures of accuracy used are the mean seed spacing and the mean seed spacing within the target range (inside region 2 only). The first is strongly affected by missing and double seeds and therefore must be analysed with care. The mean seed spacing within the target range gives a good indication about the seed spacing produced by the drill when it had successfully selected seeds. This measure of accuracy eliminates the influence of double and missing seeds therefore it is a good indication of the performance of the prototype in relation to seed delivery.

To evaluate the prototype's ability to accurately control seed depth, the mean seed depth and standard deviation were used.

3. Literature Review

In this literature review the subject precision drilling for precision agriculture is explored in the light of seed placement and location in the field. Firstly the benefits of producing uniform seed spacing and the development of precision agriculture technology are reviewed and secondly the development of punch planters is reviewed in view of advanced control of seed delivery, placement and location.

3.1 Uniform seed spacing and equidistant plant distribution

Plants that are uniformly spaced in the field have a more efficient use of water, nutrients, light and possible other environment parameters (Colville and Burnside, 1963). Uniform plant spacing is important for several crops and is a crucial factor for crops like sunflower, maize and sugar beet.

Robinson et al. (1982) measured the effects of uniformity of plant population on sunflower seed yield, plant growth, and seed quality. Uniformly spaced single plants lodged least, produced heads of lowest moisture percentage at harvest and produced seed of highest yield and oil percentages. Yield reduction from uneven plant distributions averaged 10%. The yield advantage from uniform spacing might have been greater with mechanised harvest because of a relatively higher potential for harvesting losses from lodged plants. Their data support continued effort to improve planting techniques and equipment.

A survey of with-in-row variability in maize plant spacing in fields, in three Kansas counties, indicated that plant spacing precision could increase yields from 200 to 1,200 kg/ha without changing planting rates (Krall et al. 1977). Shubeck and Young cited by Krall et al. (1977) showed that random staggered planting pattern that approached equidistant planting out-yielded conventional drilled maize by 800 kg/ha. Hoff and Mederski (1960) compared two maize planting patterns, conventional 42-inch row spacing and equidistant planting (the same distance between rows and between plants within the row) at several plant populations. Equidistant spacing increased the yield of maize in almost all experiments and also provided a uniform vegetative canopy early in the season that may reduce soil erosion. Glenn and Daynard, cited by Molin et al. (1996), investigated plant spacing uniformity at the desired population.

Uniform plant spacing is crucial for yield and quality of sugar beet. With uniform spacing the plants can grow to a uniform size and fill the row space without being pushed out of the row by its neighbour. A uniformly distributed crop promotes vigorous competition against weeds and also facilitates the work of harvesters, which operate more efficiently harvesting beet with uniform diameters (Jaggard, 1990). The efficiency of the drilling operation is becoming increasingly important because drills have been handling progressively more expensive seeds. For sugar beet it is vital to achieve a well-established and uniform plant population (Ecclestone, 1998).

Maj Olsen et. al. (2002) conducted a field experiment to determine the effect of three densities (204, 449 and 721 plants/m^2) and two spatial patterns (normal rows and a uniform grid pattern) of spring wheat (*Triticum aestivum* L. cv. Leguan) on interspecific competition with six weed species. The results showed highly significant effects of both crop density and spatial distribution in the ability of the crop to suppress weeds. Overall, the total weed biomass was 30 % lower when the crop was sown in a uniform grid pattern than crop sown in traditional rows.

Taylor and Younie (2002) observed that a spring oats crop has a better ability to compete with weed when drilled at a squarer pattern and plants more widely spaced within narrower rows gave more uniform ground cover.

Superior performance for a more uniform plant distribution for winter wheat was observed by Johnson et al. (1998) when evaluating different seed rates and two row spaces. Narrow row spacing (0.10 m) yielded 8% more than wider row spacing (0.20 m) at similar seed rates. In narrow row spacing plant distribution gets closer to a square pattern. Similar results were obtained by Joseph et al.(1985). A yield increase of 33%

(average of three seed rates) was described by Holliday (1963) after reducing row spacing from 20 to 10 cm. Marshall and Ohm (1987) also obtained significant yield increase between 5.3 and 6.8% for narrower row spacing when evaluating 16 winter wheat cultivars planted at 6.4 and 19.2 cm row spacing.

Wheat yield evaluation in weed-free and weed-infested fields were conducted by Solie et al. (1991) to verify whether equalizing average plant spacing within the row and in between rows would increase yield. Decreasing row spacing significantly increased yield in both weed-free and weed-infested fields. There was a 14% increase in yield when row spacing was reduced from 23 to 7.5 cm.

Heege (1993) compared drilling, band sowing, broadcast sowing and precision drilling performance for cereals, rape and beans. The best seed distribution over an area with bulk-metering methods was obtained by broadcast sowing. Precision drilling could surpass this distribution only when a small row-spacing was used to produce an equidistant seed spacing pattern. As seed rates are reduced for cereals a triangular or square seed distribution becomes more feasible as wider rows are needed.

3.2 Reduced seed rates for wheat

Whaley et al (2000) evaluated the physiological response of winter wheat to reductions in plant density. The results showed that September sown winter wheat is able to maintain yields at plant densities as low as 125 plants m^{-2} and that it achieves this through increased radiation capture per plant, enhanced radiation use efficiency and better partitioning of assimilates to the ear.

Spink et. al. (2000) investigated the mechanisms of yield compensation to reduced plant density in winter wheat as affected by sowing date. The average economic optimum plant density was 62 plants/m^2 for late-September, 93 plants/m^2 for mid-October, and 139 plants/m^2 for mid-November sowings. These results showed that UK's current target of 250-300 plants/m^2 may be reduced to save on seed cost which represented

21.5% of the variable costs (Chadwick, 1999). Compensation for reduced population was due to increased shoot number per plant, increased grain number per ear and to a lesser extent increased grain size.

Early drilling wheat has been proposed as an alternative to increase farmers margins. Seed cost is reduced using low seed rates and yield may be increased expanding the crop-growing period. Early drilling also gives more flexibility to machinery use because it spreads autumn drilling dates, spring spraying windows and harvesting dates (Farmers Weekly, 1999).

David Langton (2001) evaluated various low seed rates for early drilling wheat in September. Seed rates as low as 20 seeds/m^2 were tested. A prototype of a precision drill and a conventional drill were used and the best results so far were obtained when precision drilling at 60 to 80 seeds/m^2. Tiller count averaged eight for the precision drilled wheat sown at 60 seeds/m^2 and about four for a typical commercial seed rate of 120 to 150 seeds/m^2 for September. At 60 seeds/m^2 the plant stems were much thicker and the ears were significantly longer with more spikelets. Savings on seed costs ranged from £7.50/ha to £13.00/ha for the Clair variety and £36.00/ha to £62.00/ha for a hybrid wheat. The author highlighted the following advantages of low plant density uniformly spaced in the field: better standing ability that reduces lodging, reduced spread of disease due to less root and plant contact, more vigorous root development with increased access to nutrients, better drought tolerance and a more even canopy that is more efficient intercepting light.

There is a growing interest in reducing seed rates for several crops, including cereals, but uniform seed spacing is not sufficiently accurate with a conventional drill. Plants grow more vigorously when less crowded however accurate seed spacing and depth are crucial to gain the full benefit. The development of a precision drill that places wheat seeds with a high level of accuracy could be an important step towards using reduced seed rates commercially. Precision drills usually have a 20% slower working rate than conventional drills (David Langton, 2001). This limiting factor and the extra cost related to precision drilling needs to be overcome by savings in seed cost. It is also important for a precision drill designed for wheat to achieve a precise and reliable performance when used for minimum tillage and direct drilling (David Langton, 2001).

3.3. Accurate seed placement and location for precision agriculture

Crop production systems can be categorized in scales ranging from individual plants to population of plants, field, farmsteads, county, eco-region and country. Precision agriculture technologies have been used to improve both economic and environmental sustainability of crop production systems, worldwide. A field is subdivided into small management units and information about soil, yield, nutrients and water, for example, can be disaggregated. Modern information technologies allow the producer to obtain detailed information of the entire farm with sufficient data to successfully manage the land at a fine scale and the ultimate goal would be to look at agricultural fields as a collection of individual plants (National Research Council, 1997).

Site-specific chemical weed control is an area of precision agriculture in which the field has been treated at a fine scale. It can save a substantial amount of herbicides because weeds generally appear in patches (Häusler and Nordmeyer, 1999). Herbicides savings using site-specific chemical weed control can be as high as 70% (Nordmeyer and Dunker, 1999). Weed treatment maps are usually used to guide chemical application. Generally these maps are created based on field observations and demand a considerable amount of labour. Remote sensing and near-ground imaging or sensing are attractive alternatives to make weed maps (Lippert and Wolak, 1999)(Chapron et al., 1999)(Vrindts et al., 1999)(Rew et al., 1999) (Yang et al., 2000) but there are difficulties in distinguishing between crop and weed.

Tillett et. al. (1998) tested an autonomous robotic system for plant-scale husbandry to demonstrate individual plant treatment. An imaging system was used to provide guidance information and a segmentation was completed using image intensity, size and geometry to pick up crop plants requiring treatment. The authors suggested that a secondary independent location system, used as a back up system, would improve safety and reliability under variable light conditions and variations within the field. It was also suggested that if a GPS is used combined with machine vision technology it would be economically advantageous to explore spatially selective operations while collecting data for field maps.

Non-chemical weed control methods, like site-specific mechanical weed control (mechanical weeding), is another area that needs development to achieve a better weed control and a significant reduction in herbicide use (Gerhards et al., 1999). Søgaard and Olsen (1999) used a system with a colour video camera for determination of the location and direction of crop rows. The system was still under development and the degree of accuracy of the row detection program was not measured. Miller (2000) reviewed the progress on precision agriculture technologies identifying research needs mainly for sensing crop conditions. Imaging systems alone were judged to be limited for weed detection because of over-lapping of leaves. Some systems that could cope with this problem were slow and expensive.

Tillett et. al. (2001) developed a computer vision technique for automatically estimating the number of crop and weed plants and the area that they cover, using prior knowledge of planting geometry. The crop chosen was transplanted brassica because plants are well spaced between and within the row. Weed numbers were increasingly underestimated as weed density rose. Weed area were underestimated by 0.48% of a total image area and crop plant area were underestimated by 1.12%.

The yield response of sugar beet to transplanted weeds with respect to the distance between beet and weed and an aboveground weed cutting at various growth stages was investigated by Heisel et. al. (2002). The authors concluded that "precise detection of the position of the sugar beet or the position of weeds in the row is necessary for efficient mechanical weed control in the row. A system combining geo-referenced seeds with Real Time Kinematics - Global Positioning System and a sensor or computer-vision for single plant detection were proposed to reconstruct the individual positions of a plant and make robotic steering of weeding device". Results indicated the importance of removing the weeds closest to the beet, therefore a precise and reliable system is needed to mechanically remove weeds without damaging the crop (Heisel et. al, 2002).

Chamen (2002) identified technologies for plant and row detection and guidance systems based on the required accuracy for plant and row scale operations. Due to significant advances in technology, absolute positioning systems were considered as well as systems which detect plants or rows. The main advantage of absolute systems is to determine where a row or a plant is in the field, and to identify this position repeatedly. The combination of machine vision and the Differential Global Positioning System (DGPS) with enhancement using Real Time Kinematics (RTK) showed the greatest potential for plant and row detection and guidance. Machine vision systems and DGPS can achieve peak errors of as little as ± 35 mm and ± 40 mm, respectively Chamen (2002). The later is currently expensive but should become cheaper. There is also potential for using DGPS as a guidance system to improve precision while drilling.

Bleeker et al. (2002) tested fingerweeders, a torsionweeder, a rotary weeder and a powered spike harrow to control intra-row weeds. Good results were obtained for some conditions but more research was recommended to avoid plants being uprooted and yield reduced. These systems relied on better crop anchorage than weeds to work and still cause significant losses.

The combination of GPS, imaging systems and accurate seed maps may be used to boost reliability and accuracy of machine location in the field for precision agriculture. Seed locations shown in the map would act like beacons as the imaging system detects plant locations. If each punch-planter unit rotates independently the seed distribution left in the soil by the drill will be unique (like a fingerprint) at every location. If the GPS signal is lost for some reason machine location may still be possible based on the accurate seed map previously produced using post-processing techniques.

Accurate seed placement and location, geo-referencing seeds have been identified as useful tools for precision agriculture technology. A seed map combined with computer vision may prove to be a reliable system to locate crop and weed plants for site-specific chemical control and mechanical weeding. Furthermore, seed position maps combined with other precision agriculture technologies, could be used to monitor the performance of the drill, to determine germination for monitoring crop development, and to guide site-specific fertilizer applications, for example.

Seed maps can also show where over and under drilling has occurred. Accurate skip maps, showing positions where the drill had failed to place a seed, can be produced based on seed position maps. These maps could be used combined with yield maps to investigate any influence on yield that might have be caused by plant populations below or above the target population of plants. For instance, over drilled areas like the headlands have lodging problems that reduce yield.

Cordesses et al. (1999) studied and implemented an all GPS-based harvester controller. The first tests produced promising results. An interesting characteristic of this type of system is the ability to operate efficiently at night or under low visibility. Seed maps may prove useful to enhance the performance of harvesters. For example a speed reduction might be necessary in over drilled areas, less populated areas might allow higher speeds. Different functions of the harvester could also be automatically tuned according to plant population.

Site-specific applications of fertiliser is another activity that may benefit from precise seed placement and location in the field. When using a combined drill, the relative position between seeds and fertiliser may be kept fixed at an optimum position. The rate of fertiliser application could be optimised accordingly to soil conditions while keeping optimum distance between seeds and fertiliser.

3.4. Measuring seed positions in the field

There are two main difficulties to be overcome while accurately locating seed positions in the field. The first one is to precisely measure the position of the drill in the field and the second is to measure the exact seed position on the ground in relation to the planter.

The combination of both measurements gives seed position in the field. It is important to use systems accurate at a sub-centimetre level because seed maps would require high level of accuracy to be valuable for plant-scale operations. A seed position error of ± 15 mm seems to be a reasonable target to be achieved.

To measure the position of the machine in the field, GPS systems exhibit the most promising properties (Stoll and Kutzbach, 1999). RTK-GPS systems have a standard deviation from the mean of approximately one centimetre (Cordesses et al. 1999). Because seed location maps are not needed in real time, improved accuracy may be obtained using post-processing techniques.

The European Union approved the development of its own global navigation satellite system – Galileo –on 26th of March 2002. The system is a joint project between the European commission (EC) and the European Space Agency (ESA). The high price of these systems is expected to go down as its use and the competition among the receiver manufacturers increase. The system will use dual frequency as standard to deliver a real-time positioning down to the metre range, which is unprecedented for a publicly available system. Higher levels of accuracy will also be available. The system is under development and its accuracy was not specified yet. Differently from the American GPS, the accuracy of Galileo will be guaranteed. Galileo will compete with GPS commercially but will also complement it and provide redundancy. It will be inter-operable with GPS and GLONAS, the American and Russian military controlled systems, but will be under civilian control. With Galileo the number of satellites available from which to take a position will more than double (European Space Agency, 2002).

The system has been developed for high levels of reliability to be suitable for applications where safety is crucial. The Galileo system will consist of 30 satellites, 27 being operational and 3 being active spares. The Galileo navigation signals will provide a good coverage even at latitudes up to 75 degrees north. High accuracy in global positioning will be viable even in places where buildings, mountains or trees obscure signals from satellites low on the horizon. It will inform users within seconds of a failure of any satellite. The loss of one satellite will have no discernible effect on the user (European Space Agency, 2002).

For a planter to be able to measure seed positions in the field, the path followed by each seed from the metering unit to the soil needs to be well controlled. Kocher et al. (1996) developed an opto-electronic system to measure seed spacing uniformity detecting front-to-back location of seed drop. The seed sensor used had 24 pairs of LEDs/phototransistors. This system was further developed and evaluated by Lan et al. (1997). The size of the phototransistors was reduced to improve sensor sensitivity mainly for small seeds. The results obtained from both electronic systems were highly correlated with measurements obtained using a grease belt test stand. Panning et al. (1997) used this system in a laboratory evaluation and compared the results with seed spacing obtained in a field evaluation. The results indicated that the opto-electronic system could not predict seed spacing in the field because of seed bounce and roll in the furrow.

3.5. Improving precision during drilling

When comparing broadcasting, drilling, precision drilling and punch planting an increased precision on seed distribution is evident. Broadcasting produces random seed spacing in all directions. While drilling seed spacing within the row is still random but row spacing is uniform. Precision drilling produces more uniform seed spacing within the row but there are still small random errors caused by seed bounce and roll in the furrow. Punch planting has the potential of producing equidistant seed spacing in all directions because seed delivery and placement at a specific point in the soil is well controlled and can be measured. Several drilling units can be synchronized to produce a desired pattern of seed distribution in the soil like a triangular or rectangular distribution.

An analogy between electronic and planting systems helps to clarify some potential advantages of a punch planting system. Digital electronics are more reliable than analogue electronics because in a digital system the effects of noise and interference are drastically reduced. Digital systems use only two easily distinguishable voltage levels so these systems do not have to generate or sense precise voltage values, they just need to distinguish between two voltage levels. Consequently, it is much easier to consistently obtain a required operating performance from a large number of circuits using digital electronics. Faults will not often occur through variations in the performance of components. This is not true for an analogue system where the effects of unwanted noise and interference signals degrade the signals reducing reliability (Green, 1999). Seed bounce and roll in the furrow may be eliminated using a punch planter in a similar way that noise and interference were eliminated in digital electronics.

3.6. The development of punch planters

A punch planter is a machine that opens a hole in the soil and delivers a seed into it. The concept of punch planting is very interesting because seeds are trapped inside holes promoting a good seed soil contact mainly for conservational techniques as minimum tillage and direct drilling. Precise seed spacing can be achieved if holes are opened uniformly in the soil and seed are successfully delivered into these holes.

A substantial amount of research has been done in the last three decades to develop punch planters that are precise and reliable. Several concepts were proposed but a design robust enough to be extensively applied has not been developed. The main problems encountered in the development of these machines were poor seed delivery mainly at high speeds, punch clogging, and difficulties to adjust seed spacing. An overview about the development of punch planters that includes pictures is shown in appendix A.

Punch planter concepts were categorized in three distinct groups, according to seed delivery and hole punch timing. In the first group holes are punched in the soil before seeds are delivered into them. In the second, seeds are delivered first, to then be pressed into the soil later. In the third group hole punching and seed delivery are done simultaneously. Chronologically, the developments started with the first group moving toward the third. The development of the second group overlapped in time with the end of the first group and beginning of the third group.

3.6.1.Punch planters that open holes in the soil before seed delivery

The concept of first opening holes in the soil to later receive seeds was the first step in the development of punch planters. Various mechanisms that press the soil to open holes in the soil were developed, including rotational and reciprocating ones. For this group of punch planters three concepts were reviewed.

Jafari and Fornstrom (1972) developed a precision punch planter for sugar beet that used a wheel with solid punching cones to open holes in the ground by compression. A seed metering unit located behind the punch wheel selected single seeds that were delivered by gravity into the holes. To vary seed spacing the number of wheel punches had to be changed and the metering unit had to be timed again. The prototype was tested in clay loam and sandy soils. The average seed placement in holes varied from 97.6 % at 4.8 km/h to 94.0 % at 8 km/h. The standard error of seed placement varied from 0.056 % at 4.8 km/h to 0.066 % at 8 km/h. The average seed spacing varied from 29.2 cm at 4.8 km/h to 29.8 cm at 8 km/h. The standard error of seed spacing varied from 0.58 cm at 4.8 km/h to 0.53 cm at 8 km/h. Seed depth was judged uniform but no data was presented These results should be analysed with care because hole size was not mentioned. The development of this punch planter had a great value encouraging further attempts. A similar machine was developed by Srivastava and Anibal (1981) for precision planting navy bean. An air jet seed delivery system was added to the concept to boost seed delivery in combination with gravitational seed delivery. This concept was abandoned after some preliminary tests because variations in hole spacing, caused by unequal cone penetrations, made external seed delivery impossible. This result is conflicting with the previous development.

An intermittent punch planter that uses a pneumatic cylinder to punch holes in the soil was developed by Heinemann et al. (1973). As the punch penetrates the soil it activates a seed dropper mechanism which delivers a seed into the hole as the cylinder makes its return stroke. The punching mechanism was actuated by a reed switch circuit that opened the cylinder valve. Magnets attached to a packing wheel activated the reed switch to control seed spacing. Seed spacing was adjusted changing the number of magnets on the wheel. The seed dropper was made of a vertical rotating wheel with slots (seed cells) that was moved one notch at a time by a ratchet. The seed-drop mechanism was built for 3.5-mm diameter spheres simulating pelleted seeds. Several adjustments were necessary on the planter for matching seed delivery time to travel speed. The prototype was tested for coated sugar beet seeds. The soil type and speed used during the experiments were not reported. The hole size was adjusted to 38 mm deep, 8 mm wide and 13mm long. The percentage of holes, which received a seed was 85 %. The remaining 15 % that did not receive a seed could have either missed the hole or were not delivered. Uniform ground speed was a critical factor in delivering the seeds into the hole at the proper time. This concept was the only one found that uses a reciprocating punch mechanism.

Heinemann et al. (1973) also developed a punch planter concept using a belt that runs over the soil. The belt was internally riveted to two chains that run on two pairs of sprocket wheels at each end of the planter. A wheel with articulated punches radially attached to it was installed between the front pair of sprocket wheels. These punches entered eyelets uniformly spaced in the belt before entering the soil. As the punch wheel continues to rotate the punches penetrate the soil. The soil is kept in place by the belt as the punches leave the soil. A seed drops onto the belt as each punch was removed from the belt eyelet. The seed was then brushed along the belt until it fallen through the eyelet, which remained over the hole in the seedbed. The seed metering unit was similar to the seed-drop mechanism described for the pneumatic punch machine described above. Punch carriers on the front wheel actuated this unit. A prototype was not constructed therefore this solution was not evaluated. This concept was basically a suggestion to solve the problems with external seed delivery found during the previous punch planter development. A perforated belt was placed over the holes made in the soil to guide seed delivery and placement.

Delivering seeds after opening the holes in the soil proved to be a very difficult task to be accomplished. Therefore this first group of punch planters were not successful and other concepts had to be developed. At 8 km/h, a point on the planter, for example the seed releasing point, remains above a 2.5 cm hole in the soil for just 11.25 msec.

3.6.2. Punch planters that deliver seeds before pressing them into the soil

This group of punch planters explores, in quite different ways, the concept of putting a seed on the punch tip and then pressing it into the soil. In this manner, seed delivery into a small hole in the soil (which had deteriorated the performance of previous solutions) could be eliminated. Seed soil contact was notably improved by this group of punch planters. Three distinct rotary punch planters are reviewed. The first uses magnetic punches to hold iron coated seeds before pressing them into the soil. The second uses vacuum and the third uses a wheel with cells to hold the seeds on the tip of the punches.

A two row punch planter with magnetic punches was developed by Wilkins et al. (1979) for lettuce seeds that were previously coated with iron oxide. Seeds were transferred by magnetic force from a seed wheel to the tip of cylindrical magnetic punches articulated on the periphery of a wheel. As the wheel continues to rotate the punches firmly imbed the seed into the soil. The strength of the soil surrounding the seed pulled it from the punch. The prototype was tested in a Chualar sandy loam soil at 1.6 km/h and 3.2 km/h. For 1.6 km/h, one seed was found in 98.3 % eliminating completely double seed. For 3.2 km/h, one seed was found in 88.3 % without double seed as well. No other measure of accuracy of seed placement was presented. The missing seeds were due to faults on seed selection. Seeds were effectively attracted by the magnetic punches. Tests showed that the punch planter system resulted in a shorter time between planting and emergence than when a conventional planter was used.

An experimental punch planter which uses vacuum to hold seeds on the tip of the punches was evaluated by Bufton et al. (1986) for pelleted and non-pelleted seeds. Truncated hollow cones were radially mounted in a wheel. Seeds were transferred externally to the tip of these punches using a synchronised movement between the punch wheel and a seed drum operated by vacuum. At the point of transference seeds were ejected from the drum by air jet and held at the tip of the punch by vacuum. They were pressed in the soil as the wheel rotated. When the punch had fully penetrated the soil the vacuum was interrupted so the seed remained inside the hole as the punch left the soil. The prototype was tested for pelleted lettuce and natural cabbage seeds. The target spacing was 15.0 cm but wheel-skid made it increase to 16.5 cm. The drill was judged unsuitable for sowing non-pelleted cabbage seeds because of seed damage, however the punch planting system improved emergence of pelleted lettuce seeds when compared with two commercial drills. The machine was operated at a maximum speed of only 1.8 km/h during this evaluation.

Brown et al. (1994) developed a high-speed punch planter to operate up to 7.2 km/h pressing seeds into the soil. It has 24 cylindrical punches that were radially housed in a punch wheel. The punch wheel was driven by a lay shaft using a V-belt drive. When the wheel rotates, the punches moves radially inward and outward actuated by a cam. Each punch moves inward to create a cavity inside the wheel and receive a seed that was previously selected. At this point an external shoe prevents seeds from falling prematurely on the ground. At the end of the shoe the punch moves rapidly outward to press the seed into the soil. A mechanical seed metering unit for pelleted and naturally round seeds was developed to be housed inside the punch wheel. It was installed at one side of the punch plane. A selection ring with seed cells in front of each punch rotated at the same speed as the punch wheel. Seeds were transferred sideways from these cells into the cavities in the punch wheel using an air jet. Seed spacing could be varied by changing the cell ring. The minimum seed spacing achievable was 5 cm and it could be varied to 10, 15, 20, 30, 40 and 60 cm dividing the total number of punches in the wheel by the sub-multiples: 2, 3, 4, 6, 8 and 12. Another solution was proposed to obtain all multiples uses a pulsing air jet for seed transfer that would be electronically controlled. The prototype was tested for lettuce seeds in a sandy loam soil. Additional experiments were conducted with sugar beet, brassica, onions, leeks and parsnip. No measures of accuracy of seed placement were presented because the objective of the research was to investigate potential advantages of punch planting in improving emergency compared with a coulter drill.

The main limitation of this group of drills, which presses seeds into the soil is the complexity of the concepts developed. In general they have a high number of moving parts that work without lubrication and in contact with the soil. Sliding joints, which have an inherently poor performance when not lubricated frequently and sealed from the environment, were widely used. Seed damage is a concern, furthermore, this concept is not suitable for conservation techniques like direct drilling because seeds could not be pressed over a residue cover and into a harder soil. These factors discouraged further developments of this type of punch planter. The next group of punch planters explores the concept of delivering seeds internally at the same time that the hole is being opened. Usually a hollow punch which is used to open the holes is also used to direct seeds into the hole more efficiently.

3.6.3. Punch planters that open holes and delivery seeds simultaneously

There was significant progress in the development of punch planters when holes were opened in the soil at the same time that their respective seeds were being delivered. A better ability to operate at higher speeds was the main benefit gained through improved synchronisation between the seed metering unit and the soil opening mechanism. There was also a major change in the method that these machines open holes in the soil. This process changed from vertical soil compression in the last two groups of punch planters to a combination of lateral and vertical compression of the soil. This change was crucial to expand the application of the concept for conservation techniques like direct drilling and for plastic mulch covered beds.

A considerable effort in developing this group of punch planters has been evident in the last two decades. Several machines which uses rotating punch wheels are reviewed. Several developments used the same concept, which was embodied in different ways.

Srivastava and Anibal (1981) developed a punch planter concept for conservational tillage to produce equidistant seed spacing of navy beans. A seed metering unit, driven by a chain drive, was integrally mounted inside a punch wheel, which had 50 delivery punches shaped as hollow cones with an involute shape at the leading edge. An air jet was used to propel seeds inside these delivery punches towards the hole being opened in the soil. The prototype was tested with plastic balls because of poor seed selection for navy beans. The first tests were conducted in a test stand. The percentage of plastic balls metered decreased as the speed increased. The prototype achieved 98 %, 93 %, 74 % and 63 % of plastic ball selections and deliveries at 1.6 km/h, 3.2 km/h, 4.8 km/h and 6.4 km/h respectively. The second tests were conducted in a soil bin. During preliminary tests in the soil bin the punch planter was pushed by hand and punch clogging was severe. This problem was solved by driving the punch wheel with an electric motor to cause some positive slip keeping the punch tips clean. Synchronising the seed releasing point for proper seed placement was critical. Hole walls collapsed before seed placement in loose dry soils. Soil type, speeds tested and measures of accuracy of seed placement were not reported. This concept was quite innovative not only because internal seed delivery was pioneered but also because the integrated construction of the punch wheel with the seed metering unit created a compact unit.

Adekoya and Buchele (1987) developed a punch planter to plant maize in tilled and untilled soils. It had a wheel, which rotated on a horizontal shaft, and 12 radially mounted punches that penetrated the soil while closed. Inside the soil, these punches were opened by a cam and after leaving the soil they were closed by a spring. A temporary resting-place at the bottom of the punch was provided to accommodate a seed before being dropped into the hole. A simple metering device, placed outside the wheel, transferred seed from the hopper into each punch as it penetrates the soil. Movement was transmitted from the wheel to the metering unit using a chain drive. The prototype was tested in an untilled clay loam soil with up to 75 % of residue cover.

The punch planter was tested at 2.9, 5.0, 6.5 and 7.9 km/h. The mean seed depth (4.3 cm) and the mean hole spacing (25.7) were independent of travel speed. Note that hole spacing was used and not seed spacing. On the other hand, the percentage of punched holes containing only one seed decreased significantly as the planter travel speed increased. Its Mean was 91 %, 79 %, 66 % and 59 % at 2.9 km/h, 5.0 km/h, 6.5 km/h and 7.9 km/h respectively. The main advancements of this solution was the punch opening mechanism that avoided clogging, the efficiency in which the punch wheel was ground driven and the uniform punch penetration obtained. The main disadvantages are the high number of moving parts that work in close contact with soil. If punch clogging occurs it might be difficult to clean.

A punch planter with few moving parts for planting maize through plastic mulch and for direct drilling was developed and evaluated by Shaw and Kromer (1987). The opening mechanism consisted of an inclined wheel with fixed spades mounted on it. As the spade wheel rotates the spades are inserted into the soil and shifted to create a cavity for a seed. The wheel axis was inclined from the horizontal to mount the seed metering device closer to the soil and to ease the entry of the spades into the soil. The wheel yawed slightly to make a cavity in the soil and also avoid dragging seeds out when the spades leave the soil. The spade wheel was directly coupled with the seed metering unit, which was placed at the centre of the spade wheel. Radial seed tubes were attached to each spade to guide seed delivery into the opened holes. The prototype was tested in an untilled clay soil at a maximum speed of 4.5 km/h but no measures of accuracy on seed placement were presented only about emergence. Seed emergence was 72.9 % when seeds were planted at 2 km/h and 74.3 % at 4 km/h. The main value of this concept is its simplicity because only one moving part is used to open holes in the soil and deliver seeds into them. The flow of energy and seed is smooth but achieving a reliable seed delivery to the bottom of the holes is a concern.

Shaw and Kromer (1989) described a punch planter for drilling vegetable seeds in plastic mulch systems. It was developed from concepts originated by growers by the Agricultural Engineering Department at the University of Florida,. The planter consisted of a punch wheel with hollow wedge shaped punches, which penetrated the mulch film and the soil underneath it to place seeds. The seed-metering device was driven from the punch wheel. As the wheel rotated, seeds were metered into a star shaped manifold, which directed them towards each punch as it approached the ground. One or more seeds were delivered into each punch where they rest for a short time. When each punch started to withdraw from the soil, the seeds were released through a spring-loaded door on the rear of the wedge. The door was opened by a lever arm activated by a fixed cam. Seed spacing could be varied by changing the number of punches on the wheel. The emphasis of this concept was on its flexibility providing a set of seed cells for different seed types and several transmission ratios to achieve a wide range of seed rates. The downside of this solution is its high number of moving parts. The authors explained that when the planter was operating in wet soil or with a high amount of plant residue, the moisture caused flat squashed seeds to stick inside the punches and some holes were not planted. No measure of accuracy was presented.

Resende et al. (1994) developed and evaluated a punch planter to direct drill maize. The concept had two punch wheels placed in a "V". These punch wheels had a fixed number of spades that were made with metal stripes. Both punch wheels were free to rotate independently driven by the ground. A fertilizer metering unit was installed at the centre of one wheel and a seed metering unit at the other wheel. The punch planter performance in relation to seed delivery was poor because the open spades failed to guide the seeds properly into their holes.

Debicki and Shaw (1996) optimised the concept developed by Shaw and Kromer in 1987. The planter had a revolving spade soil opener synchronised with a vacuum seed metering unit positioned close to the ground. A roller chain drove the seed meter from the hub of the spade wheel. The spades were hollow prisms radially mounted on the periphery of a wheel (1000-mm diameter). The seed meter dropped seeds through the spades when they were in the position to form cavities in the ground. The prototype was tested for soybean, maize and sugar beet during laboratory evaluation. Optimum location and synchronisation parameters between the seed meter and the punch wheel were found. The timing angle had to be adjusted for each seed type and for high and low speeds of operation. The performance of the punch planter was evaluated in the field for maize seeds in a sandy soil. The prototype was tested for two seed depths (25 and 50 mm), two spade types, two timing angles (24° and 31°) and three speeds (1.5, 3.0 and 5.0 km/h). Plant spacing and standard deviation were the only measures of accuracy presented. The mean plant spacing at 5 km/h was 217 mm and the standard deviation was 15 mm. Seed spacing was slightly dependent on planting depth for one type of spade due to variable spade wheel slip. Seed spacing was independent of spade type, travel speed and seed discharge points.

Molin et al. (1996) designed and evaluated a rotating punch planter for direct drilling exploring the same concept used by Shaw and Kromer (1987) and Debicki and Shaw (1996). The design was based on maize requirements. The planter made cycloidal holes by an inclined wheel aided by a yaw angle. A base ring was used as support for 15 punches radially bolted to the ring. The external tip diameter was 650 mm. A commercial vacuum seed metering was used. The punch wheel shaft powered the seed metering shaft using a chain drive with a transmission ratio of two to one, because the seed metering used a 30-cell disc for maize. The punches had an offset funnel shape with 70 mm wide on the top and 30 mm wide on the tip. The seeds were transported from the seed metering unit to the soil inside the funnel punches by gravity. Field tests were conducted in a silt loam soil under no till conditions. The prototype was tested for soybean and maize seeds at 7.2 km/h. Seed depth was set to 4 cm. Two different residue covers were used and three residue amounts to test the effect of the residue cover on the performance of the machine. There was no significant difference (5 % level) between these treatments, therefore the residue types and amounts did not influence the performance of the punch planter. The quality of feed index, the missing index, the multiple index and precision were used as measures of accuracy on seed placement. The quality of feed index varied from 62.9 % to 74.6 %, the missing index varied from 20.0 % to 26.1 %, the multiple index varied from 5.4 % to 14.3 % and precision varied from 11.1 % to 12.8 %.

Molin et al. (1997) modified the prototype built by Molin et al. (1996) using three interchangeable punch wheels with different diameters and 15 punches. The prototype was evaluated at 5.4, 7.2 and 9.0 km/h for three punch wheel sizes at three no-till plots.

The soil type was a silt loam. The results for this field evaluation are shown in Table 7.1, where quality of feed index, missing index, multiple index and precision are presented for comparison. The smaller punch wheel (diameter of 650 mm) had the best performance but in general the punch planter had a good performance. The following changes were strongly recommended. The side doors at the tip of each punch should have their height decreased to less than the minimum planting depth to prevent seeds from dropping out of the holes. A customised seed metering unit with the same angular speed as the punch wheel was recommended to eliminate synchronisation failures. A rubber wheel was added (Figure 3.1) to the punch planter to clean the doors of the punches because during preliminary tests soil was found sticking in this area.

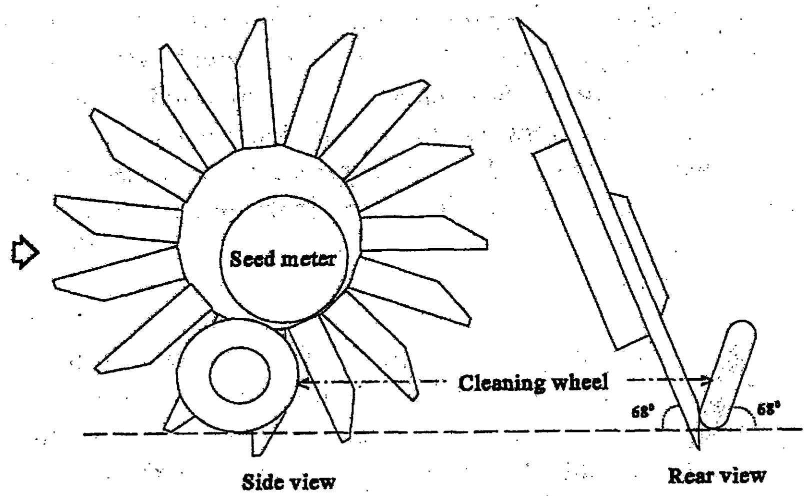


Figure 3.1: Molin et al. (1997) adapted an inclined rubber wheel to clean the punch tips and openings.

During the development of punch planters in the last three decades several concepts were created, developed and evaluated. The concept of using an inclined wheel with fixed punches, which incorporates a seed metering unit, seems to be the most successful mainly because of its simplicity (one moving part). It has shown good potential to operate at high speeds and for use in conservation techniques but some problems still remain. In order to develop a punch planter robust enough to be widely adopted, seed delivery and placement needs to be further improved, punch clogging needs to be avoided efficiently. Varying seed spacing within the row has been a difficult task to be accomplished by rotary punch planters and a simple way to vary seed spacing needs to be developed.

4. Punch planter design

The design of the precision punch planter started with the specification of the requirements that the solution should satisfy.

The conceptual design was the second step in which the concept was developed. During this phase, a function structure was established to formulate the problem independently of the solution principle. Working principles to execute these functions were searched for and combined to create ten solution variants. The solutions were then expanded in various directions to explore the potential of distinct working principles. Solution variants were then evaluated and one concept was selected to be developed.

The layout and shape of components were developed during the embodiment design phase. The most challenging task was to develop a solution to vary seed spacing while keeping the systems simple. A working cardboard model was constructed to help in developing the layout of the machine and also to develop solutions to auxiliary systems.

During the detail design, manufacturing and assembly drawings were made and materials were specified. A prototype unit of the precision punch planter was manufactured and built based on these drawings.

4.1. Precision punch planter design specification

The requirement list for the precision punch-planter is shown in table 4.1. It explains the requirements to be satisfied by the solution being developed. These requirements were classified into ten groups: geometry, kinematics, force and energy, seed, safety, production and assembly, operation and ergonomics, maintenance and agronomic. Each individual requirement was classified as "demands" – that should be met in all circumstances or "wishes" - that should be considered whenever possible.

Table 4.1: Requirement list for a precision punch-planter

D ⇒ demands W ⇒ wishes	Requirements list Precision Punch Planter for Cereals
	1. Agronomic
D	Suitable for conventional, minimal tillage and no till systems
D	Seed rates from 50 to 400 seeds/m^2
D	Seed depth – from 2 to 10 cm
	2. Geometry
D	Capable of producing equidistant seed spacing in all directions
D	Minimum row spacing using parallel units = 160 mm
D	Minimum row spacing using offset units arranged in two rows = 80 mm
D	Seed spacing within the row (3, 6, 9, 12, 15 and 18 cm)
W	Compact drilling unit: 600 x 120 x 500 mm (length, width and height)
	3. Kinematics
D	Travel speed: 8 km/h or faster
W	Eliminate seed bounce and roll in the soil at all speeds
D	Minimise seed bounce and roll inside the hole (± 5mm around centre)
D	Maximum seed flow at 8 km/h: 74 seeds/second (seed spacing of 3 cm)
D	Able to precisely synchronize movement among punch planter units
	4. Forces and Energy
D	Unit weight 50 kg ± 5 kg
W	Minimise drawn force
W	Produce a smooth flow of energy and seeds
	5. Seed
D	Precision drill wheat and other cereals
W	Precision drill other types of small seeds
D	Precisely control seed delivery allowing measurement of seed positions
	6. Safety
D	Use safe systems and protect dangerous points
D	Robust and reliable components and mechanisms
	7. Production and Assembly
D	Small number of components and simple to manufacture
D	Achieve high precision with reasonable tolerances
D	Use as many components bought out as possible
W	Easy assembly using just a few tools
	8. Operation and Ergonomics
D	Precise and reliable operation
D	Resistant to dust and the elements
D	Easy to control and adjust its mechanisms
W	Easy to charge and discharge seeds
	9. Maintenance
D	Low and easy maintenance services using few tools
W	Easy and fast cleaning
W	Easy to inspect and lubricate

Preferably requirements were quantified but qualitative aspects were considered. The requirement list was established at the start of the design process and was continuously updated with fresh information generated throughout the development of the machine.

4.2. Conceptual Design of a Precision Punch-planter

4.2.1. The Establishment of a Function Structure

The search for solutions was facilitated by breaking down the complex function of "drill seeds" into simpler sub-functions like: "open holes", "meter seeds", "deliver seeds", "close holes" and "press soil". A function structure was built to express the relationship between these sub-functions independently from the solution to be adopted. This function structure is shown in figure 4.1.

Sub-functions were classified as main and auxiliary functions. The main functions serve directly the overall function "drill seeds". The auxiliary functions have a complementary nature, but they have a strong influence on precision and reliability. Control functions were considered as auxiliary functions.

The flow of seeds among these sub-functions is also represented in figure 4.1. The flow of seeds starts when seeds are charged into the machine. Following this seeds are stored, selected and delivered to be placed in the soil. Seeds not used may also be discharged.

A significant flow and conversion of energy is needed in order to perform several distinct sub-functions. These functions need to be executed in a synchronized way. Therefore, energy conversion and control are crucial functions that must be executed by the solution being developed.

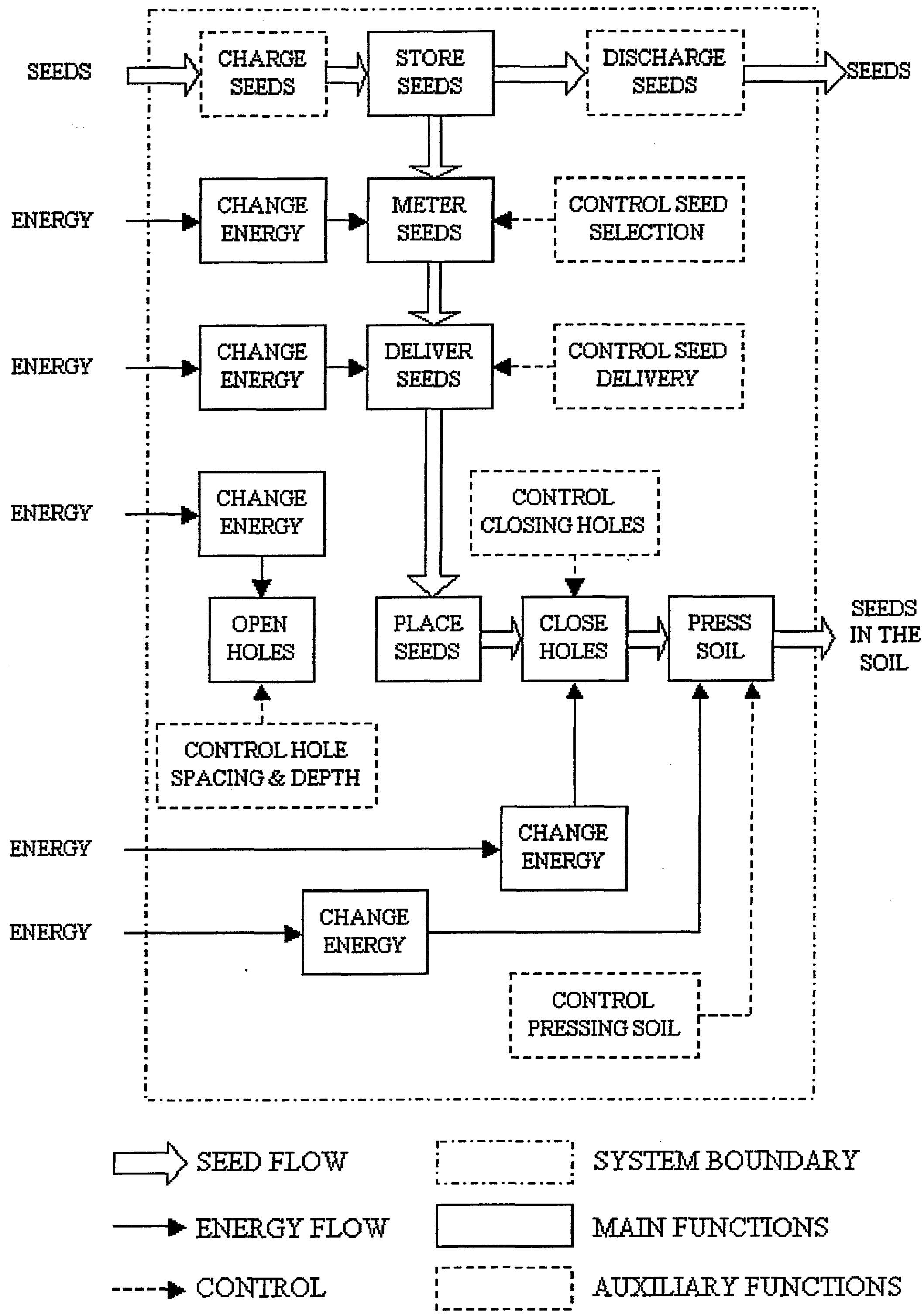


Figure 4.1: Function structure for a precision punch-planter

4.2.2. Searching for working principles

Once a function structure had been established the search for solutions for every sub-function started. This search was based on the literature review and precision drill catalogues. These catalogues were an important source of information because it is a source of well-tested solutions for a collection of functions. New solutions were also created with the objective of solving problems found in the development of previous planters.

These solutions (working principles) were illustrated in a morphological matrix where sub-functions were organized in rows and working principles for these sub-functions were organized in columns (see figure 4.2.). Elements illustrated in this matrix are described below.

Row A (meter seeds) shows types of seed metering units: perforated belt type, air jet type, finger type, spoon type, cell drum type, vacuum type and sloted disc type.

Row B (change energy for meter seeds) shows: a ground wheel, an electric motor, a hydraulic motor, a spiked wheel, the PTO of a tractor and a rubber track as energy converters.

Row C (control seed metering) shows: a mask disc that covers some holes of the main disc, a seed disc with multiple rows that could be turned on and off, a seed disc with variable rotational speed, interchangeable seed discs and seed discs arranged in series that could be turned properly to adjust seed selection.

Row D (deliver seeds) shows a seed being delivered by: gravity, centripetal force, air and water jet, mechanical impact, rotating hollow punches with suction and a rotating mechanism.

Row E (control seed delivery) shows seeds being delivered guided by a funnel, a tube parallel walls, vertical channel and unsupported.

Row F (open holes) shows a vertical punch, a rubber track, translational punches, a wheel with solid punches, a punch wheel with articulated punches that penetrate a perforated belt, an inclined punch wheel and a wheel with multiple opening mechanisms - one for each punch.

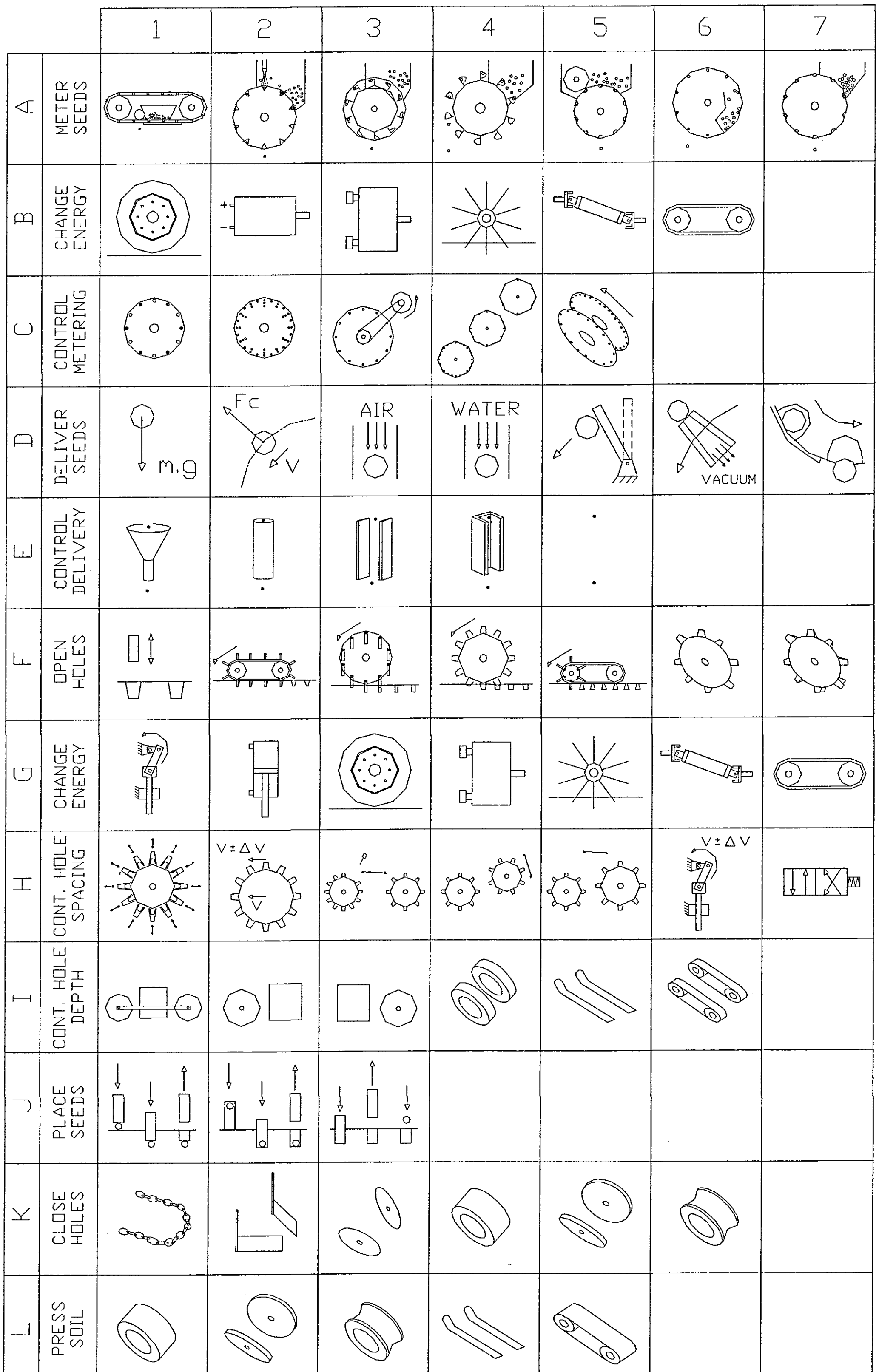


Figure 4.2. Morphological matrix showing working principles for sub-functions.

Row G (change energy for opening holes) shows a crank mechanism, a pneumatic cylinder, a wheel, a hydraulic motor, a spike wheel, the PTO and a rubber track.

Row H (control hole spacing) shows a punch wheel with variable diameter, a punch wheel with controlled speed, a punch wheel with variable number of punches, a number of punch wheel units, interchangeable punch wheels, a crank mechanism with controlled speed and a pneumatic valve as working principles.

Row I (control hole depth) shows different arrangements for wheels and other supports to control working depth.

Row J (place seeds) shows basically three different ways of placing seeds: before, during and after hole opening.

Rows K (close holes) shows some devices to close holes.

Row L (press soil) shows some possible solutions using wheels, skis and rubber track to compact the soil.

4.2.3. Combining working principles to develop conceptual variants

The working principles shown in figure 4.2 were combined to make several conceptual variants. Distinct ideas were explored to create ten solution variants that are shown on figures 4.3 to 4.12. While developing these conceptual variants attention was concentrated on fundamental functions like: open holes, control hole spacing, meter seeds, control seed selection, deliver seeds, control seed delivery and place seeds. The objective of concentrating on these functions was to reduce the number of possible solutions. Other functions like: store seeds, close holes, and press soil would only be considered in the following phase – the embodiment design. To expand the search for solutions in various directions a range of rotating, translating, pulsating and crawling mechanisms were considered for opening holes in the soil. The collection of working principles for each variant was selected to provide mechanical advantages when combined together. This was an effort to boost the strength of distinct solutions. While selecting the seed metering unit for a particular solution preference was given to a vacuum type because it is the most successful principle for irregular shaped seeds.

Therefore most of the solutions developed were fitted with a vacuum seed metering unit.

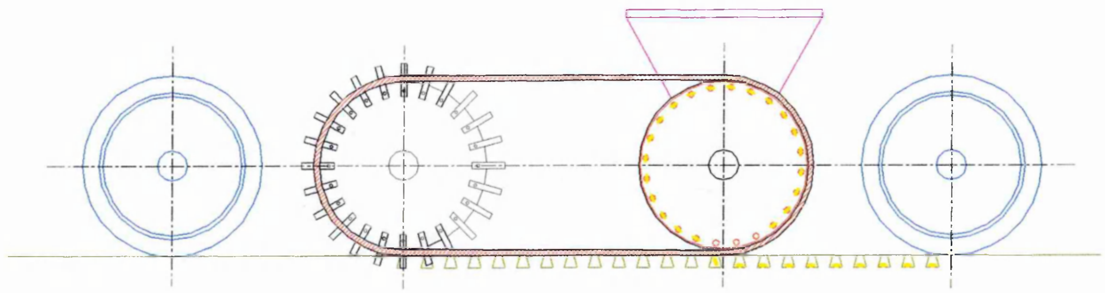


Figure 4.3. Solution variant #1

Variant #1 (Figure 4.3) has a punch wheel with articulated punches that penetrate a perforated belt before entering the soil. This mechanism produces a bell-shape hole in the soil. The belt holes remain above the holes in the soil as the machine is moving. A vacuum type seed metering unit select seeds that are delivered into these belt holes Seeds are horizontally accelerated to facilitate seed delivery by gravity. To increase seed spacing some holes do not receive a seed.

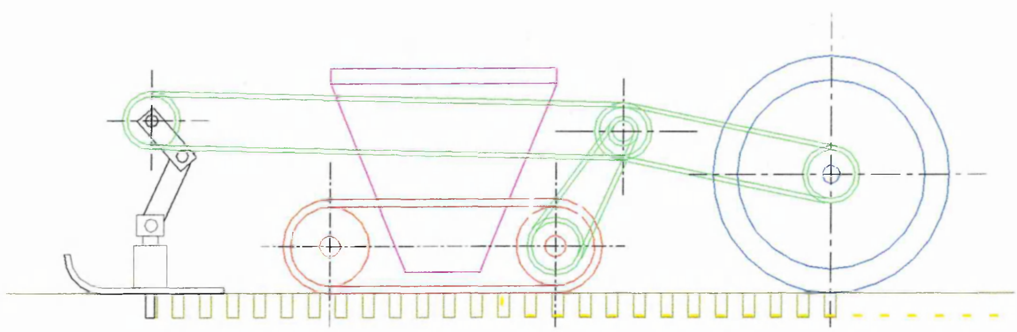


Figure 4.4. Solution variant #2

Variant #2 (Figure 4.4) has a reciprocating punch mechanism actuated by a crank to open holes in the soil. A belt type seed metering unit selects seeds to be delivered inside these holes by gravity. The meter was placed close to the soil to facilitate seed delivery. The seed metering unit has its speed synchronized with the reciprocating mechanism. To vary seed spacing these mechanisms have the ratio between its rotational speed and the land wheel speed varied.

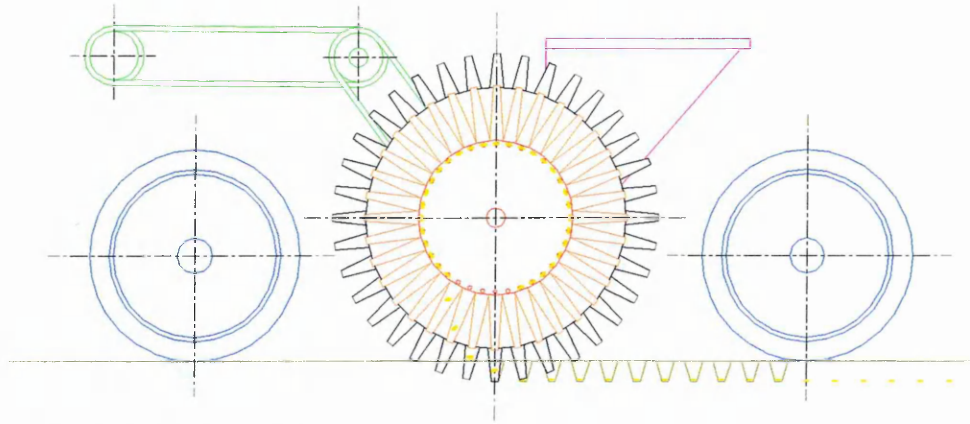


Figure 4.5. Solution variant #3

Variant #3 (Figure 4.5) has double punch wheels positioned in a "V" to open holes in the soil. When the punches penetrate the soil its shape changes from a closed-shape to an open-shape. Holes are created in the soil starting from its centre line towards its periphery. The tip of opposite punches always move away from each other while inside the soil. Double punch walls are used creating a labyrinth seal at the interface region between the punches avoiding soil clogging and clear the way for seed delivery. A vacuum type seed metering unit located in the centre of one punch wheel selects seeds to be radially delivered inside hollow punches. To vary seed spacing the number of active punches is varied and some opened holes may not receive a seed. It is also possible to control punch wheel rotation to slightly vary seed spacing.

Variant #4 (Figure 4.6) has a punch wheel with solid cones arranged radially to open holes in the soil. Punch wheel rotational speed is controlled to adjust hole spacing continuously within a range. Behind the punch wheel, a belt type seed metering unit

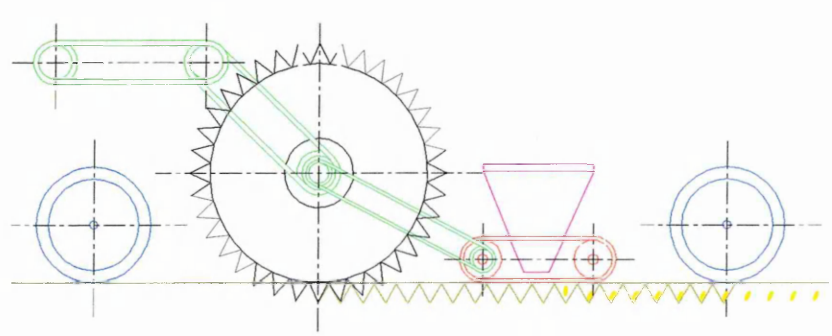


Figure 4.6. Solution variant #4

located very close to the ground selects seeds to be delivered by gravity. The metering rotational speed is synchronised with the punch wheel speed. To adjust seed spacing in steps seed selection is controlled and some holes may not receive a seed.

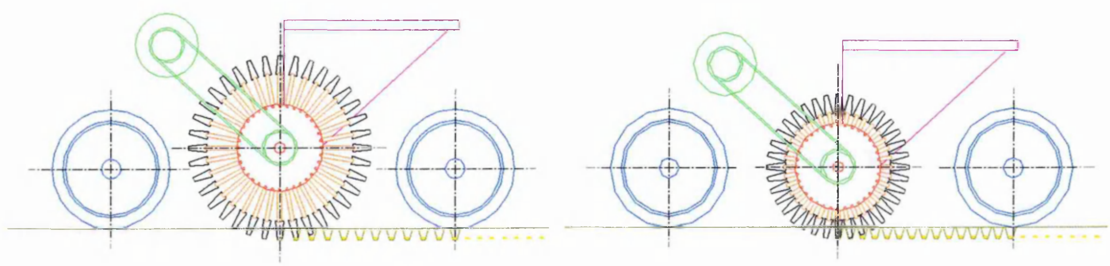


Figure 4.7. Solution variant #5

Variant #5 (Figure 4.7) has one inclined punch wheel with variable diameter to open holes in the soil. Controlling the size of the punch wheel hole spacing can be infinitely varied within a range. A vacuum type seed metering unit selects seeds that are radially delivered through hollow punches. The seed disc rotates at the same speed as the punch wheel.

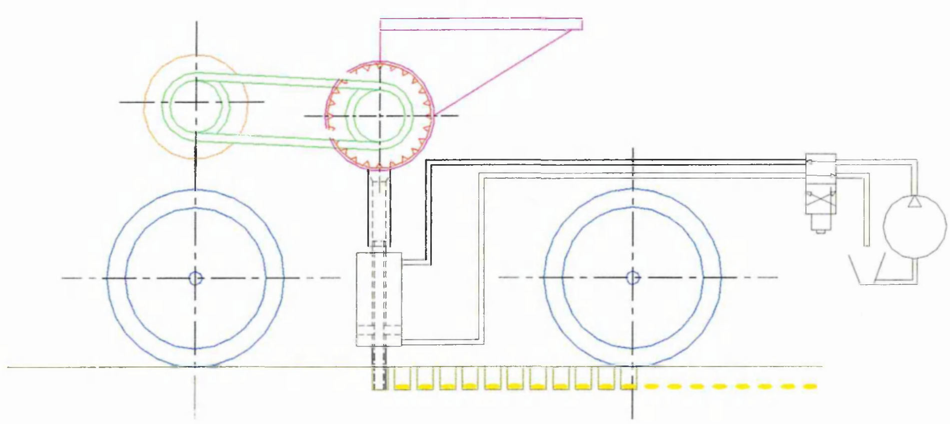


Figure 4.8. Solution variant #6

Variant #6 (Figure 4.8) has a reciprocating punch mechanism actuated by pneumatic cylinder to open holes in the soil. A seed metering unit uses a rotating cylinder with conical holes radially arranged to select a collection of seeds. An air jet is then directed to these conical holes to remove the excess leaving only one seed inside. This remaining seed is then delivered through a hollow punch using air jet and gravity. The oscillatory movement of the pneumatic cylinder and the rotational speed of the seed metering unit are controlled by computer to vary seed spacing.

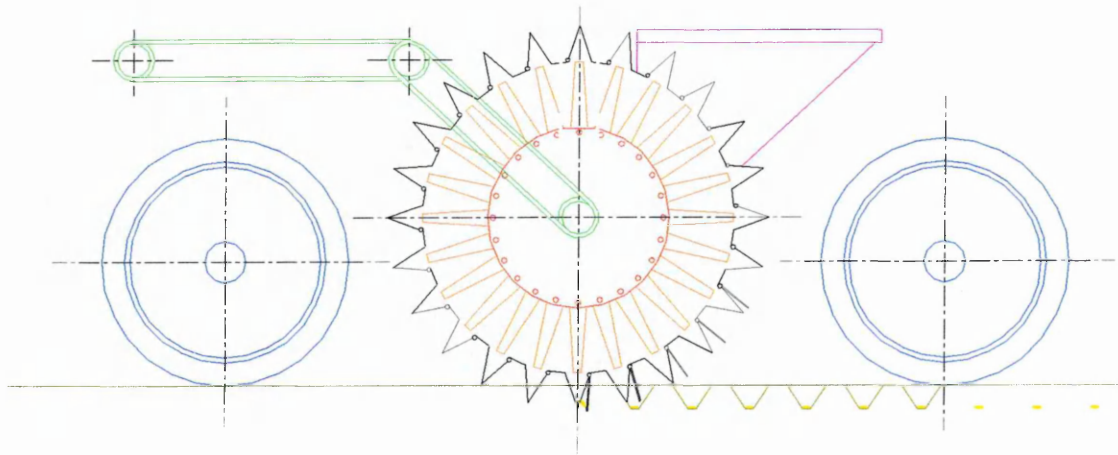


Figure 4.9. Solution variant #7

Variant #7 (Figure 4.9) has one punch wheel with articulated mechanisms to open holes in the soil. A vacuum type seed metering unit selects seeds to be radially delivered. Seed spacing is controlled by adjusting the punch wheel rotational speed or changing the number of active punches.

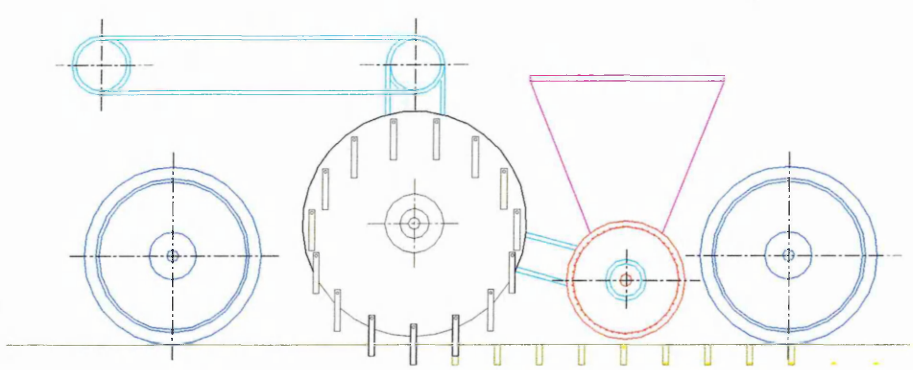


Figure 4.10. Solution variant #8

Variant #8 (Figure 4.10) has one punch wheel with articulated solid punches that are always vertically orientated when they penetrate and leave the soil. A vacuum type seed metering unit selects seeds that are externally delivered by gravity into the opened holes. Seed horizontal speed is adjusted to match ground speed, facilitating seed delivery. To vary seed spacing some holes are left without seeds.

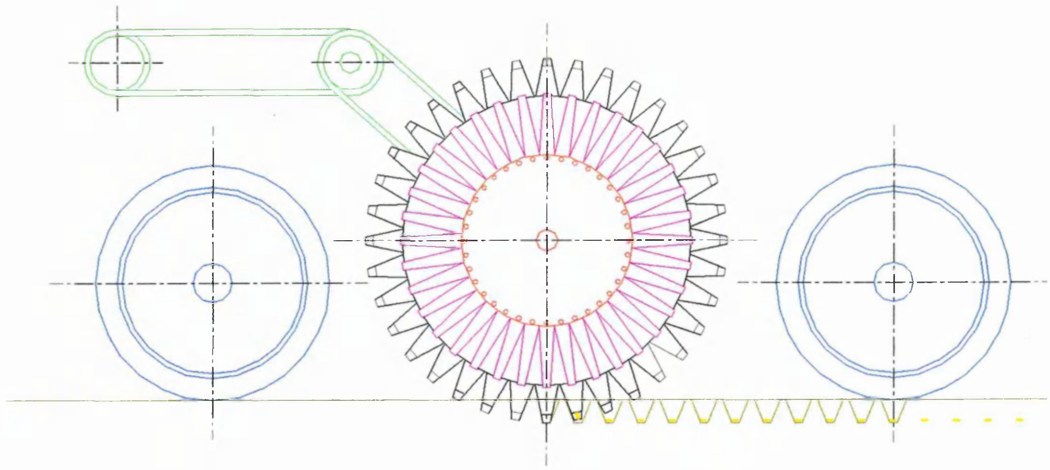


Figure 4.11. Solution variant #9

Variant #9 (Figure 4.11) has one inclined punch wheel with fixed hollow punches to open holes in the soil. A vacuum type seed metering unit selects seeds to be internally delivered. Seed spacing is adjusted by controlling seed selection therefore the number of active punches.

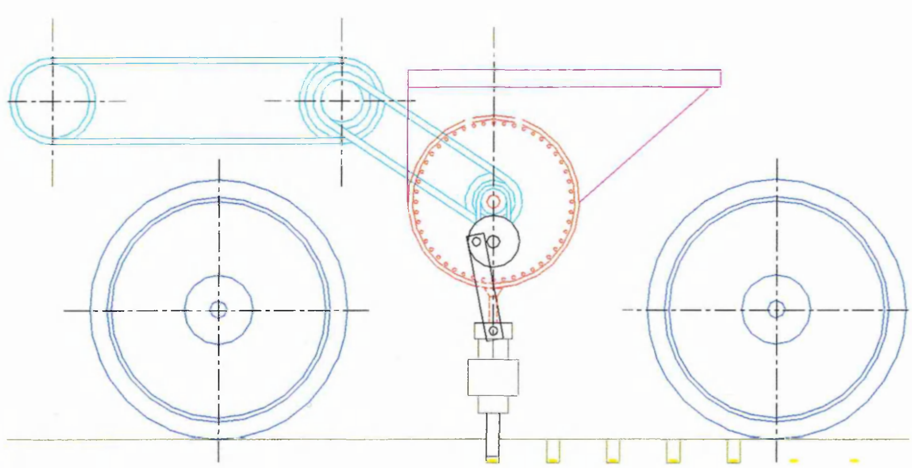


Figure 4.12. Solution variant #10

Variant #10 (Figure 4.12) has a reciprocating opening mechanism operated by crank to open holes in the soil. A vacuum type seed metering unit selects seeds to be internally delivered using a hollow punch. Seed spacing is adjusted by controlling the rotational speed of the crank in relation to ground speed.

4.2.4. Evaluating conceptual variants

The solution variants previously developed were evaluated in order to find the best solution. The first part of this evaluation was to establish evaluation criteria and its weighting factors. Later, values were assessed for all solution variants. The value scale adopted for this evaluation is shown in Table 4.2.

The choice of evaluation criteria was completed in accordance with the requirements specified in the beginning of the design process. An evaluation tree was created to facilitate the assignment of the relative importance of each evaluation criterion. This tree is shown in Figure 4.13. The criterion in the left column – reliable and precise – is the main criterion. It has a relative weight and a total weight equal to one. These values are shown in the bottom of its box. This criterion was broken into four sub-criteria: good operational characteristics, reliable operation, precise operation and simple production which form the second level of this tree. Weighting factors between 0 and 1 were then allocated to each criterion according to its relative importance. The sum of all weights equals one. These four criteria were broken down into more criteria to make the third level of the tree. The fourth level was created in the same way. Each evaluation criterion from the fourth level has its weight calculated by multiplying the individual weight for itself by the individual weight for related criteria from superior levels.

Table 4.2 Value scale for conceptual evaluation of variants

Points	Meaning
0	Absolutely useless solution
1	Very inadequate solution
2	Weak solution
3	Tolerable solution
4	Adequate solution
5	Satisfactory solution
6	Good solution with a few drawbacks
7	Good solution
8	Very good solution
9	Solution exceeding the requirements
10	Ideal solution

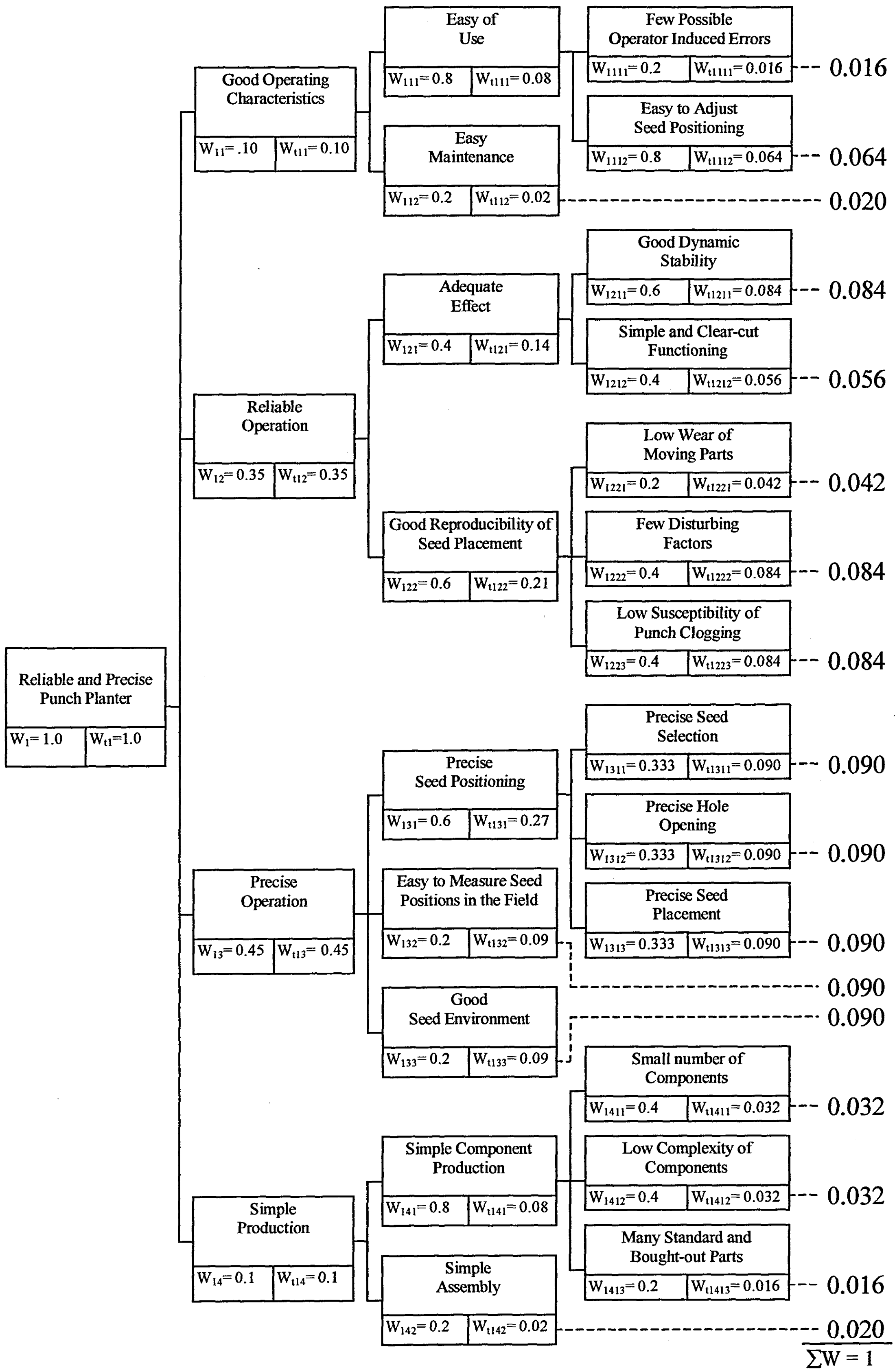


Figure 4.13: Objective tree for conceptual evaluation

The evaluation of variants 1 to 5 and variants 6 to 10 are shown in Table 4.3 and Table 4.4 respectively. Conceptual variants were evaluated accessing values for every parameter, according to the value scale shown in Table 4.2.

Table 4.3: Evaluation of conceptual variants #1, #2, #3, #4 and #5.

Evaluation Parameter			**Variant #1**		**Variant #2**		**Variant #3**		**Variant #4**		**Variant #5**	
No	**Parameter**	**Wt.**	V_{i1}	WV_{i1}	V_{i2}	WV_{i2}	V_{i3}	WV_{i3}	V_{i4}	WV_{i4}	V_{i5}	WV_{i5}
1	Few possibilities of operator errors	0.016	3	0.048	1	0.016	7	0.112	3	0.048	10	0.160
2	Easy to adjust seed positioning.	0.064	2	0.128	1	0.064	6	0.384	1	0.064	7	0.448
3	Easy maintenance	0.020	3	0.060	2	0.040	9	0.180	4	0.080	3	0.060
4	Good dynamic stability	0.084	5	0.420	2	0.168	9	0.756	3	0.252	5	0.420
5	Simplicity of functioning systems	0.056	5	0.28	3	0.168	9	0.504	9	0.504	4	0.224
6	Low wear of moving parts	0.042	3	0.126	2	0.084	8	0.336	7	0.294	3	0.126
7	Few Disturbing factors	0.084	3	0.252	2	0.168	9	0.756	3	0.252	6	0.504
8	Punch shape that avoid clogging	0.084	8	0.672	10	0.840	7	0.588	10	0.840	3	0.252
9	Precision of the seed metering unit	0.090	8	0.720	3	0.270	8	0.720	3	0.270	8	0.720
10	Precise hole shape and hole spacing	0.090	3	0.270	5	0.450	8	0.720	9	0.810	5	0.450
11	Precise seed delivery	0.090	2	0.180	1	0.090	9	0.810	1	0.090	6	0.540
12	Seed positions can Be easily measured	0.090	2	0.180	1	0.090	9	0.810	1	0.090	7	0.630
13	Good seed environment	0.090	4	0.360	4	0.360	9	0.810	4	0.360	7	0.630
14	Small number Of components	0.032	3	0.096	7	0.224	8	0.256	6	0.192	2	0.064
15	Low complexity Of components	0.032	4	0.128	4	0.128	8	0.256	8	0.256	3	0.096
16	Many standard and bought-out parts	0.016	6	0.096	8	0.128	7	0.112	8	0.128	3	0.048
17	Simplicity of Assembly	0.020	4	0.080	6	0.120	8	0.160	9	0.180	2	0.040
		Σw_i= 1.0	OV 68 R 0.40	OWV 4.096 WR 0.410	OV 62 R 0.36	OWV 3.408 WR 0.341	OV 138 R 0.81	OWV 8.270 WR 0.827	OV 89 R 0.50	OWV 4.71 WR 0.471	OV 84 R 0.49	OWV 5.412 WR 0.541

Table 4.4: Evaluation of conceptual variants #6, #7, #8, #9 and #10.

Evaluation Parameter			Variant #6		Variant #7		Variant #8		Variant #9		Variant #10	
No	Parameter	Wt.	V_{i6}	WV_{i6}	V_{i7}	WV_{i7}	V_{i8}	WV_{i8}	V_{i9}	WV_{i9}	V_{i10}	WV_{i10}
1	Few possibilities of operator errors	0.016	10	0.160	5	0.080	4	0.064	7	0.112	10	0.160
2	Easy to adjust seed positioning.	0.064	9	0.576	3	0.192	3	0.192	5	0.320	9	0.576
3	Easy maintenance	0.020	4	0.080	3	0.060	6	0.120	9	0.180	5	0.100
4	Good dynamic stability	0.084	3	0.252	7	0.588	3	0.252	6	0.504	4	0.336
5	Simplicity of functioning systems	0.056	4	0.224	4	0.224	9	0.504	9	0.504	6	0.336
6	Low wear of moving parts	0.042	3	0.126	4	0.168	7	0.294	9	0.378	3	0.126
7	Few Disturbing factors	0.084	4	0.336	7	0.588	3	0.252	6	0.504	5	0.420
8	Punch shape that avoid clogging	0.084	2	0.168	2	0.168	10	0.840	3	0.252	2	0.168
9	Precision of the seed metering unit	0.090	8	0.720	8	0.720	8	0.720	8	0.720	8	0.720
10	Precise hole shape and hole spacing	0.090	5	0.450	5	0.450	8	0.720	5	0.450	5	0.450
11	Precise seed delivery	0.090	4	0.360	6	0.540	1	0.090	6	0.540	4	0.360
12	Seed positions can Be easily measured	0.090	4	0.360	7	0.630	1	0.090	7	0.630	4	0.360
13	Good seed environment	0.090	6	0.540	8	0.720	4	0.360	7	0.630	6	0.540
14	Small number of components	0.032	7	0.224	3	0.096	5	0.160	7	0.224	8	0.256
15	Low complexity of components	0.032	4	0.128	5	0.160	8	0.256	7	0.224	6	0.192
16	Many standard and bought-out parts	0.016	8	0.128	4	0.064	7	0.112	7	0.112	7	0.112
17	Simplicity of Assembly	0.020	4	0.080	3	0.060	7	0.140	8	0.160	7	0.140
		Σw_i= 1.0	OV 89 R 0.52	OWV 4.912 WR 0.491	OV 84 R 0.49	OWV 5.508 WR 0.551	OV 94 R 0.55	OWV 5.166 WR 0.517	OV 116 R 0.68	OWV 6.444 WR 0.644	OV 99 R 0.58	OWV 5.352 WR 0.535

On the bottom of Table 4.3 and Table 4.4 is shown, for each variant: the overall value (OV), the relative value (R), the overall weighted value (OWV) and the relative weighted value (WR).

4.2.5. Conceptual evaluation results

The overall, relative, overall weighted and relative weighted values for the conceptual evaluation is shown in figure 4.14. When the evaluation was weighted, variant number 3 obtained the highest value followed by variants number 9, 7 and 5. When the evaluation was not weighted, variants number 3 and 9 maintained its first and second positions respectively in the rank followed by variants number, 10 and 8. Variants number 1 and 2 obtained the lowest value in both cases. Therefore the conceptual variant number 3 was selected to be further developed during the preliminary and detailed designs. Conceptual evaluation is relatively subjective because it is done at an early stage of development when conceptual variants lack embodiment. Before selecting the concept, this evaluation was examined in more detail by considering the four main evaluation criteria.

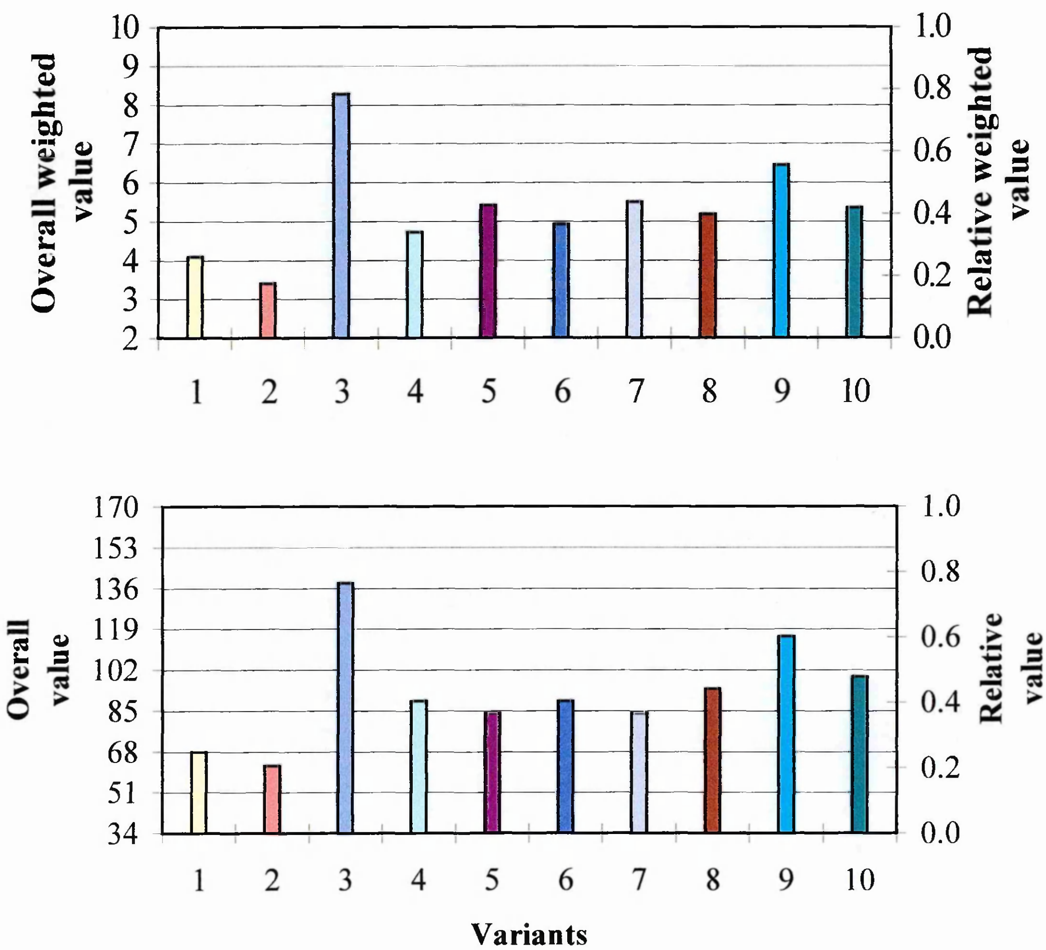


Figure 4.14: Results of conceptual evaluation of solution variants.

The relative value, the balance and the strength of each conceptual variant could be assessed in detail by combining the four main evaluation criteria in pairs (figure 4.15). An ideal concept would be placed on the top right corner of these six graphs. Higher valued solutions would be placed close to this point. On the other hand, a totally useless solution would be placed on the bottom left corner and lower valued solutions would be placed close to this point. An ideal solution and a totally useless solution are extreme cases of perfectly balanced solutions. Therefore balanced concepts would be placed alongside the line that links those two points. Extremely unbalanced solutions would be placed close to the other two corners, the top left and bottom right corners.

When all four main evaluation criteria were plotted in pairs, the relative strength and balance of variant number 3 became more apparent. Variant number 3 was the closest variant to the ideal solution in all but one of the six graphs. Variant number 9 was the strongest competitor, never being the first on the rank but remaining extremely balanced. Variant number one also was balanced but scored low values. Variants number 8 and 10 were moderately balanced and variants number 2, 4, 5, 6 and 7 were the most unbalanced concepts.

The absence of extremely unbalanced solutions is due to the process in which the solution variants were developed. Conceptual variants were created by selecting working principles in such a manner as to produce some mechanical advantage out of the combination of principles. This approach was necessary to reduce the number of possible combinations to a practical value. Otherwise thousands of conceptual solutions could be generated by combining all working principles.

Variants number 3 and 9 seems to be the best two concepts not only because they were respectively first and second on the evaluation rank but also because they are balanced solutions. Variants number 5, 7, 8 and 10 are the best of the rest, being very close to each other on the evaluation rank. Variants number 8 and 10 were more balanced than the other two. This variants number 3, 9, 10 and 8 were the most promising solutions and were selected to be examined more deeply in order to make the final selection of the concept.

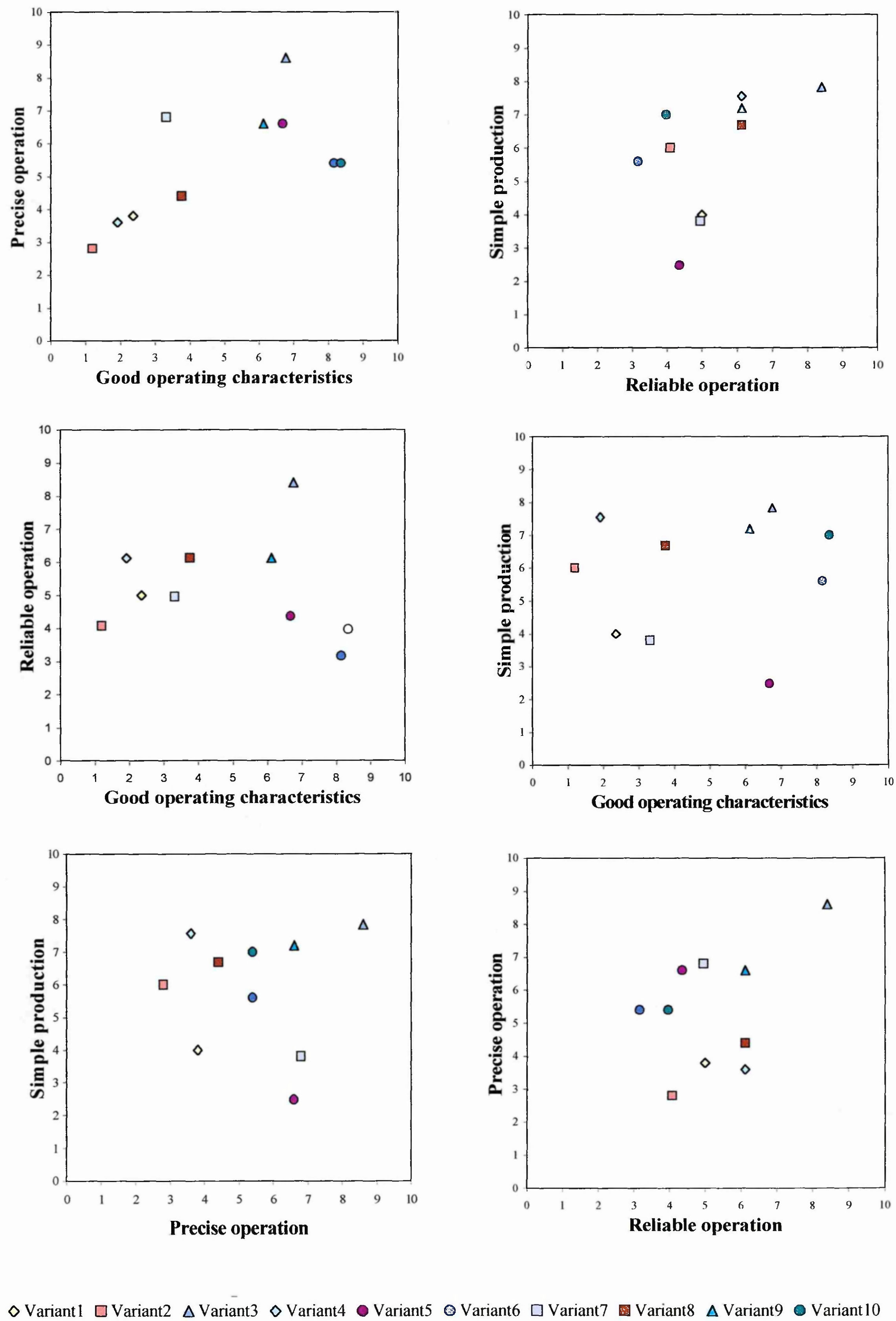


Figure 4.15: Conceptual variants comparison using the main evaluation criteria.

4.2.6. Critical analysis of the most promising concepts

The four variants previously selected were further investigated to check which one is the best concept to be developed. This measure was taken in an effort to minimise the risk of rejecting promising ideas due to evaluation faults. Following this, a comment about variants number 8, 10, 9 and 3 was made, exploring their main advantages and disadvantages.

- Concept number 8

Variant number 8 (figure 4.10) was the sixth in the rank. The strength of this concept is the hole shape it produces and the weakness is its external seed delivery.

This concept has a smooth flow of energy and is moderately simple. It produces translational movements of punches, therefore punches penetrate, remain and leave the soil vertically orientated. As a result cylinder shaped holes are produced, minimising soil disturbance. There is no soil clogging problems because the punches are solid. A vacuum seed-metering unit makes seed selection of irregular shaped seeds very efficient.

This concept places seeds in the holes after the opening mechanism leaves it. This external seed delivery is the main disadvantage of this variant because it has proved to be very difficult to be accomplished. Internal seed delivery is also difficult to implement in this concept, which would become susceptible to punch clogging.

The task of measuring seed positions in the field is very complicated to solve using this concept because seed delivery into the opened holes is not under control. Another disadvantage is caused by the principle in which holes are opened in the soil by compression. It makes the use of this solution for direct drilling impossible because trash could be dragged into the opened hole and seeds would lose soil contact. While developing the preliminary layout for this concept it was found that to produce short seed spacing more than one punch wheel would be needed to eliminate punch interference.

Using only one wheel the minimum seed spacing achievable is around 6 cm for a maximum seed depth of 3 cm. If deeper depths are needed the minimum seed spacing would become even larger. This solution uses more moving parts than the two previous concepts in its soil opening mechanism. Several rotating joints are used, therefore they must be lubricated and protected from soil contact. The problem of wasting energy, present in the previous two solutions, is also true for this solution. Varying seed spacing within the row continuously is also impossible.

- Concept number 10

Variant number 10 (figure 4.12) was the fifth in the rank. The strength of this concept is its ability to continuously vary seed spacing within the row. Its weak spot is the abrupt flow of energy and seeds that could cause precision and reliability problems. Punch clogging is also a concern because punch cleaning is difficult.

The main advantage of using a reciprocating mechanism with internal seed delivery is the ability to vary hole spacing continuously Therefore seed spacing could be controlled in the same way, by controlling the relationship between the ground speed and the mechanism speed. The seed-metering unit which uses air pressure for seed selection matches very well with the reciprocating mechanism. The opening mechanism used is relatively simple, using a small number of parts.

Seed delivery is probably the weakest point of this concept because it must happen very fast. To achieve a theoretical seed rate of 321 seeds/m^2 while producing an equidistant seed spacing distribution, a seed spacing of 6 cm and a row spacing of 5.2 cm are needed. Considering a travel speed of 8 km/h (2.22 m/s) there will be 37 seed deliveries per second inside a single hollow piston. Therefore, each seed must be delivered within 0.02702 seconds to be correctly placed in the soil when the punch tip remains at its lower position. This problem is inherent of reciprocating mechanisms. Rotating punch wheels can perform several functions simultaneously providing extra time to perform every function including seed delivery.

The flow of energy is abrupt requiring extra strength from the material used. These pulsating loads also encourage vibration, which may affect the performance of this concept. Holes are opened by soil compression making it difficult to be used for direct drilling because trash can be dragged into the opened hole. Because the bottom of hole in the soil is compacted , roots may find it more difficult to develop.

When the reciprocating mechanism input shaft is driven at constant rotational speed the mechanism generates an elongated hole orientated at the same direction as the machine travels. The longer the seed spacing set-up the more elongated these holes become. Punch clogging and cleaning are other concerns because they strongly influence precision and reliability.

- Concept number 9

Variant number 9 (figure 4.11) was the second best solution evaluated. This concept is similar to the concept number 3, however it is even simpler making it a strong competitor. The precision and reliability of this solution is a concern because of punch clogging.

This concept is extremely simple because it uses only one rotating part to accomplish several tasks. The flow of energy and seeds is smooth and seed selection is efficient.

Because variant number 9 uses only one inclined punch wheel, holes are opened in the soil from one edge to the other passing through the centre of the hole. As a result there is no protection for the punch openings that may be in contact with soil. Consequently precision, reliability and the ability to measure seed positions in the field is reduced. to avoid punch clogging, punch openings need to be designed relatively larger for this concept than for concept number 3. Consequently, holes opened in the soil would be larger, causing detriment to precise seed placement. If punches get clogged, reliability would obviously be reduced due to poor seed delivery and placement. Punch cleaning is also difficult because its mechanism does not opens after leaving the soil like in variant number 3. To clean punch openings, Molin et al (1998) added another moving part to this concept - a rotating rubber wheel - in a similar arrangement that variant number 3 has between its two punch wheels. Another disadvantage of variant number 9 is caused by lack of symmetry. The inclined punch wheel generates a lateral force, increasing loads applied to parallelogram linkage and the chassis. Therefore more material needs to be used to resist this extra load.

This concept can not vary seed spacing continuously and it wastes some energy because sometimes more holes than needed are opened.

- Concept number 3

Variant number 3 (figure 4.5) was the best solution according to the evaluation. This concept has a strong potential to achieve high levels of precision and reliability while keeping its mechanisms simple.
wall
The use of rotating mechanisms that execute several tasks simultaneously guarantee a smooth flow of energy and seeds, which is desirable for this machine. This concept uses only two moving parts to accomplish several crucial tasks, therefore it is an extremely simple solution. The double punch wheels arranged in a "V" opens holes in the soil in an efficient way. Punches penetrate the soil while closed and always open inside it, making the holes from the centre towards the edge of the hole. This concept uses redundant punch walls to increase reliability avoiding soil clogging. If punches get clogged the mechanism is wide open after leaving the soil, allowing cleaning. Punches have a strong ability to penetrate the soil and the residue cover. In relation to seed selection this concept uses a vacuum seed metering unit which is an excellent principle for selecting irregular shaped seeds. It is relatively easy to measure seed positions in the field using this concept because the seed path is under control of a rotating mechanism until the seeds reach a specific point in the soil. Hole size may be relatively smaller, increasing precision on seed positioning.

Seed delivery using a rotary punch planter is very different from seed delivery adopted for precision drills which open a furrow in the soil. A number of precision drills use fixed seed tubes that do not touch the soil, therefore they cannot control seed movement at the moment of seed placement in the soil. Concept number 3 guides seeds from the metering unit to the soil using several rotating seed tubes that actually are the delivery punches. During seed delivery the tip of the seed tubes remains inside the opened holes to efficiently place seeds in the soil at a specific locations.

This concept cannot vary seed spacing within the row continuously but it can do it in small increments. This is the main disadvantage of this variant. Another disadvantage is related to waste of energy because sometimes more holes than necessary are opened in the soil. This problem is not too significant because it will still be better than most precision drills, which waste more energy opening a continuous furrow in the soil.

4.2.7. Conceptual variant selection

Concept number 3 was therefore selected to be further developed based on the evaluation results. This selection was supported by the previous analysis in which the four most promising variants were explored for their strong and weak features.

Variant number 3 is actually a development of the second strongest concept, variant number 9. Variant number 3 has the same working principle of variant number 9 but it was duplicated to gain several benefits. The principle of using redundant systems was applied to enhance precision and reliability, and the principle of symmetry was applied to improve stability. All these benefits were gained at the expense of using just one more rotating punch wheel, keeping the solution simple.

Punch clogging has been a major problem of punch planters in general. The use of redundant punch wheels arranged in a "V" to open holes in the soil not only avoids punch clogging efficiently but also creates favourable conditions for seed delivery and punch cleaning if they get clogged. While the double punch wheel is rotating, opposite punches engage into each other forming a closed funnel before entering the soil. The interface region between opposite punches has double walls which work as a labyrinth seal to prevent soil from getting in contact with the internal parts of the funnel. Seed delivery and placement are also enhanced because seeds are efficiently guided by a closed tube from the metering to the bottom of the opened holes. The double punch wheel concept facilitates punch cleaning because opposite punches get away from each other as they leave the soil. The funnel shape is broken into two halves resulting in open surfaces that are much easier to clean.

Another major advantage of a redundant punch wheel is the possibility of using it to dose and deliver fertilizer in the same way that the other punch wheel selects and delivers seeds. In this way a combined drill can be developed to place fertilizer at optimum doses and accurate positions in relation to seeds.

The double punch wheel concept is symmetrical in relation to the direction of movement, therefore it gains some mechanical advantages. The lateral forces generated by each punch wheels are cancelled, increasing lateral stability and reducing the need for structural material for the parallelogram linkage and the planter chassis. The process in which holes are opened in the soil enhance seed soil contact for direct drilling. It might avoid dragging residue cover into the holes because holes are opened from the hole centre towards its periphery, clearing the central region from residues.

4.3. Embodiment design of a precision punch planter

The concept selected to be developed is an elegant solution with good potential for achieving high levels of precision and reliability. During the embodiment design the layout of the machine and the shape of components were developed by exploring this potential. Solutions to eliminate or minimise weak spots and solutions to auxiliary functions were also developed. These developments were done in accordance with the requirement list previously established.

Some crucial activities done during this phase were the development of a solution to vary seed spacing and row spacing to control seed distribution, and the development of an efficient seed delivery system to place seeds inside holes on time. A full-scale cardboard model was constructed to assist the development of the layout of the machine and the shape of components.

4.3.1. Size of holes to be opened in the soil

It was very important to design a machine that opens small holes in the soil because the smaller the hole the better the accuracy on seed placement. A hole base size of 10 x10 mm was chosen to accommodate seeds placed in any orientation. This area could be smaller, but choosing a hole too small would increase the risk of seeds being removed from the holes by the departing punches. This choice was a trade-off where a certain amount of precision was lost, in compensation for increased reliability. Hole depth can be varied to control seed depth accordingly to the requirements.

Another option investigated was to orientate seeds vertically before placement. In this case the size of the holes opened in the soil could be reduced, enhancing precision of seed placement. This solution is more sophisticated, therefore it was left as a suggestion for future developments. It was judged more appropriate to optimise it once the basic concept and its main systems had been approved.

4.3.2. Hole spacing and seed spacing increment

The double punch wheel opens a row of holes equidistantly spaced in the soil. The concept adopted varies seed spacing within the row controlling seed selection. When a seed is selected and delivered to every hole the minimum seed spacing is accomplished. To increase seed spacing one step, only half holes opened in the soil receive seeds. To increase by another step only one third of holes receive seeds. As a result hole spacing become the same distance as the minimum seed spacing and also seed spacing increment. The strength of this solution is the simplicity of the mechanisms involved to vary seed spacing and its weakness is the lack of flexibility while altering seed spacing.

To improve flexibility while altering seed spacing a very short distance was chosen for hole spacing therefore for seed spacing increment. This approach drove the concept of punch planting close to furrow planting, however, the fundamental concept of trapping seeds inside holes at precise locations was maintained. This measure was judged appropriate for cereals which is a dense crop where seeds sometimes needed to be placed close to each other. The hole spacing and consequently seed spacing increment was set to 3 cm to make the drill able to produce a wide range of seed spaces.

4.3.3. Seed spacing

Hole spacing determines the possible values for seed spacing. For a hole spacing of 3 cm, it is possible to produce seed spacing within the row of: 3, 6, 9, 12, 15 and 18 cm for example. In this way seed spacing could be adjusted in small increments covering a wide range. Consequently it was possible to obtain low, moderate and high seed rates, covering the whole range for cereals.

This range of seed spacing covers other crops that are drilled with more space between seeds within the row, like sugar beet. When selecting the seed spacing for sugar beet, 15 or 18 cm could be used but there is no way to set seed spacing to an intermediate value. A positive or negative punch wheel slip could be used to further obtain more choice of seed spacing.

4.3.4. Row spacing

The area reserved for each drill unit during the specification is 120 mm wide. This distance is equal to the minimum row spacing if only one row of drill units is used. Row spacing can be reduced if multiple rows of offset drill units are used. Using two rows of offset drill units its is possible to reduce the minimum row spacing to 60 mm and using three rows it is possible to achieve a minimum row spacing of 40 mm.
Row spacing can be continuously adjusted above these values

4.3.5. Drilling density

Table 4.5 shows how seed spacing and row spacing can be varied to achieve the desired drilling density using single and multiple row of drill units 120 mm wide arranged in offset. The rotational movement of neighbouring drill units can be synchronized to achieve a uniform pattern of seed distribution such as a triangular or rectangular pattern.

Table 4.5: Drilling density for 1, 2 and 3 rows of offset drill units 12 cm wide.

Seed spacing (cm)	**Drilling density (Seeds / m^2)**									
	Row spacing (cm)									
	30.0	**25.0**	**22.5**	**20.0**	**15.6**	**13.0**	**10.4**	**7.8**	**5.2**	**2.6**
3.0	111	133	148	167	214	257	321	428	641	**1283**
6.0	56	67	74	83	107	128	160	214	**321**	641
9.0	37	44	49	57	71	85	107	**143**	214	428
12.0	28	33	37	42	53	64	**80**	107	160	321
15.0	22	27	30	33	42	**51**	64	85	128	257
18.0	18	22	25	28	**36**	43	53	71	107	214
Equidistant Seed Spacing	1 row of drill units - minimum row spacing = 12cm 2 rows of offset drill units - minimum row spacing = 6 cm 3 rows of offset drill units - minimum row spacing =4 cm									

Using one row of drill units it is possible to produce the recommended seed densities for early drilling of wheat. In this case, drilling density can be continuously adjusted up to 257 seeds m^{-2}. Drilling density can be continuously adjusted up to 428 seeds m^{-2} and 641 seeds m^{-2} using respectively two or three rows of offset drill units.

4.3.6. Equidistant pattern of seed distribution

Using three rows of offset drill units synchronized to produce a triangular pattern of seed distribution, it is possible to achieve five equidistant seed spacing in all directions, resulting in seed densities of: 36, 51, 80, 143 and 321 seeds m^{-2} (see table 4.5). Another five equidistant seed spacing can be obtained if drill units are synchronized to produce a rectangular pattern of seed distribution. In this case the same distance is chosen for seed spacing and row spacing.

When not using one of these 10 equidistant seed spacing it is still possible to achieve a triangular or rectangular pattern of seed distribution very close to a truly equidistant seed spacing pattern.

4.3.7. Drilling the contour of the field

While drilling straight lines, several drill units may be synchronized to produce equidistant seed spacing within the row as well as between rows. While drilling the external contour of a field, the path followed by the drill is generally a curve. Consequently the distances travelled by external and internal drill units are different. Usually conventional drills cannot correct this difference. The double punch wheel units may be allowed to rotate independently while drilling the contour of a field to achieve uniform seed spacing within all rows. External units will automatically rotate at higher speeds to travel a larger distance and internal units will automatically rotate at lower speeds. Consequently drilling density would be more uniformly controlled over these areas. However its not possible to achieve equidistant seed spacing in all directions when drill units are not synchronized.

4.3.8. Number of punches for the punch wheel

The concept adopted varies seed spacing within the row by changing the number of active punches. The punch wheel has a fixed number of punches. To achieve the minimum seed spacing a seed is delivered to every punch. To achieve a slightly larger seed spacing seed selection is altered and only half the punches receive seeds. To increase seed spacing by another step only one third of the punches receive seeds. In this way the precision punch planter can vary seed spacing in fixed steps.

Hole spacing within the row is determined by the distance between the tips of adjacent punches. In this way, seeds could be selected for: 1, 1/2, 1/3, 1/4, 1/5 and 1/6 times the number of punches. Therefore the number of punches of the punch wheels must be divided by 1, 2, 3, 4, 5, 6 and so on, resulting in a integer number. When choosing the total number of punches for the punch wheel the following numbers were selected: 12, 24, 36, 48, 60, 72, 84 and 96. Below 100, these are the only numbers that can be divided by 1, 2, 3 and 4, allowing four different seed spacing.

The number of punches for each punch wheel was set to 60 because it can be divided by 1, 2, 3, 4, 5 and 6, to produce six seed spacing within the row (two more than the others). A punch wheel with 60 punches can have 60, 30, 20, 15, 12 or 10 active punches.

4.3.9. Punch wheel diameter

Ideally the size of the punch wheel should be as large as possible to reduce the tangential speed of the seed disc which rotates with it. Large punch wheels are also desirable because its punches penetrate and leave the soil close to a vertical orientation producing a hole shape very close to the punch shape.

A punch wheel with sixty radial punches spaced at 30 mm on its periphery has a diameter of 574 mm.

4.3.10. Double punch wheel layout

The width of the double punch wheel mechanism was restricted to 120 mm, which is the maximum width allowed for each drill unit. The double punch wheel mechanism to be fitted into this space must be able to open holes with a base area of 1 x 1 cm at the moment of seed placement. The angle between the punch wheel planes was set to 12° to match the width of the punch wheel set with the maximum width permissible. The angle between the vertical line at the lower position and the punch touching point was set to 36°. This combination gives a hole base of 10 x 11 mm if a punch width of 10 mm is used.

4.3.11. Seed delivery from seed metering unit to the soil

Seed delivery inside the punches must be done very fast and in a synchronized manner. The time window when seeds must reach the soil starts when hole size becomes big enough to accommodate a seed, and finishes when the punch starts to leave the soil. If a seed reaches the punch tip too early it may be crushed between them, causing seed damage. In this case seeds may also stick in one of the punches, failing to reach the soil. If a seed reaches the punch tip too late it may be delivered outside the hole, remaining over the soil surface. The concept adopted to accomplish a fast, precise and reliable delivery relies on the use of centripetal force, gravity and air jet to aid seed transport inside the delivery punches in a positive way.

When seeds enter the delivery punches until they leave they are under the effect of centripetal acceleration. The centripetal acceleration is driven by the formula: $A_c = w^2 \times r$; where w is the angular velocity and r is the radius. The time required for seed transport inside the delivery punch is driven by the formula: $t = \sqrt{\frac{(r - r_0) \times 2}{A_c}}$; where r = final radius, r_0 = initial radius and A_c = average centripetal acceleration. Table 4.6 shows the initial , final and average centripetal accelerations for 4, 6 and 8 km/h. Also shown is the time required for seed transport inside the punch and the seed releasing point angle. This angle is measured between the punch wheel radius at the point of seed ejection and the punch wheel radius at its lower position (vertically orientated at the bottom of the punch wheel). When only the centripetal force is considered, the seed releasing point angle remains constant for every speed. As the rotational speed increases the centripetal acceleration increases at the same proportion the time required for seed delivery decreases. Seeds should be released almost 80° in advance if only the centripetal acceleration is considered.

Table 4.6: Time and seed release point angle for centripetal acceleration only.

Travel Speed	Centripetal Acceleration (m/s^2)			Time	Releasing Point
(m/s) [km/h]	Initial (r_0)	Final (r)	Average	(seconds)	(degrees)
1.11 [4]	1.50	4.30	2.90	0.359118	79.7
1.66 [6]	3.38	9.69	6.53	0.239320	79.7
2.22 [8]	5.99	17.19	11.59	0.179636	79.7

The effect of the gravitational acceleration has a significant influence on seed delivery. Seed acceleration due to gravity varies according to punch orientation as follows: $A_g = 9.81 \times \cos\beta$; where β is the angle between the vertical radius and the radius at the punch orientation during seed transport. Table 4.7 shows the combined effect of centripetal acceleration and gravity on seed delivery time and seed release point angle. When both accelerations are considered the seed release point angle became significantly smaller. The greater reduction on this angle occurs at lower speeds because seed acceleration due to gravity is significantly greater than the centripetal acceleration at the lower speeds. The values for average acceleration due to gravity are bigger for lower speeds because punches remained more vertically orientated during seed delivery when a smaller seed releasing point is used.

Table 4.7: Time and seed release point angle for centripetal and gravitational accelerations combined.

Travel Speed	Average Acceleration (m/s^2)			Time	Releasing Point
(m/s) [km/h]	Centripetal	Gravity	Both	(seconds)	(degrees)
1.11 [4]	2.90	8.67	11.57	0.179798	39.9
1.66 [6]	6.53	7.80	14.33	0.161520	53.7
2.22 [8]	11.59	7.16	18.75	0.141240	62.6

Calculations neglect friction between seed and tube. The gravity effect has a maximum error of 5 % due to simplifications used while calculating these values

To produce a more positive seed delivery an air jet is used as an auxiliary working principle to boost seed transport during delivery. This air jet also has two other auxiliary functions. It helps to clean seed disc holes after seed ejection and the internal surface of the delivery punches.

4.3.12. The construction of a full-scale cardboard model

The model shown in plate 4.1. is the delivery punch wheel. The construction of this model proved to be a useful design tool during this stage. It was used not only to help the development of the shape, size and the layout of components but also to develop new solutions. Solutions for crucial functions like: “open hole”, “control hole spacing”, “select seed”, “control seed selection”, “singulate seed”, control seed singulation”, “eject seed”, “control seed ejection”, “deliver seed, and “place seeds” were visualized and developed using this model. Only one rotating collection of parts converts energy in different ways to execute most of these functions.

Plate 4.1. Working model of the delivery punch wheel with seed metering unit

The seed metering unit mechanism is shown in detail in plate 4.2. Seeds are selected by a vacuum seed metering unit using a perforated seed disc. The selection chamber is positioned on the left middle side of the metering unit. Seeds follow a circular path to the ejection chamber that is situated on the bottom side of the seed metering unit. Between these two chambers seed singulation is done. The singulator is not shown. Immediately after the ejection chamber comes the air jet chamber, which injects air through a radial opening into the punches that have just received a seed for delivery. The metering cover is also the support for: the chamber walls, the ejector and the singulator. The external wall is an axial cylinder that is opened close to the ejector for seed transfer and in front of the air pressure chamber for air delivery. To adjust the seed ejection point the metering cover can be turned to place the ejector at the right place. When it is turned all chambers rotate therefore every function continues to be performed at the correct time and in a synchronized way. The metering cover (which is mostly transparent in this model), its components and the shaft (which can not be seen) are the only parts that remain immobile when the punch wheel is rotating.

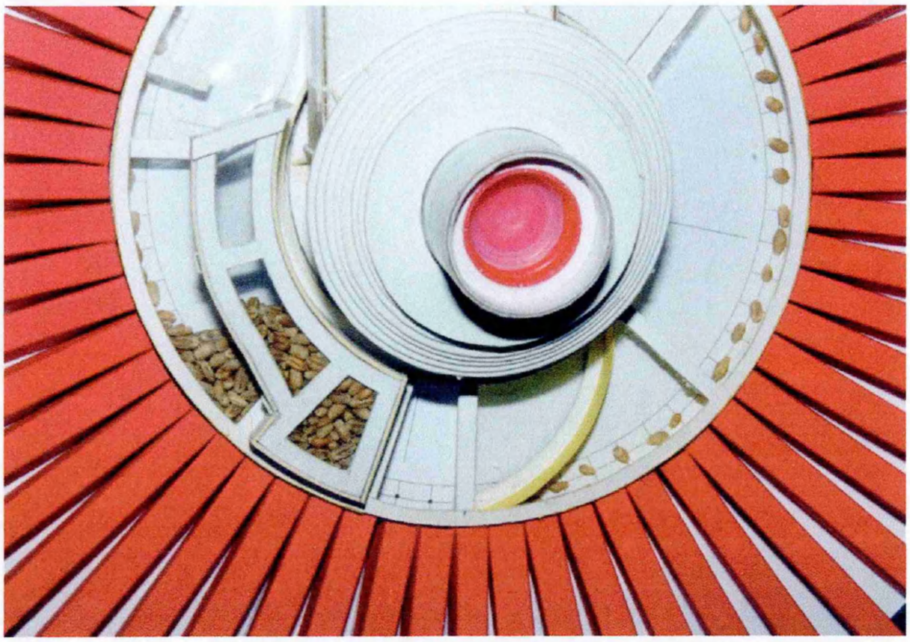


Plate 4.2.: Detail of the seed metering unit model in operation with seeds attached to the seed disc.

The cardboard model of a drill unit is shown in plates 4.3. It has two punch wheels, two depth wheels and two covering/pressing wheels all positioned in a "V". All rolling mechanisms are used to provide the drill with a good ability to follow the ground surface. The two front wheels were placed close to the soil opening mechanism for better seed depth control. This layout is more suitable for crops such as sugar beet that are planted in rows because it may increase the drills unit width if wide depth wheels are used.

It was decided to use only one depth wheel in front and another covering wheel at the back to keep drill unit width smaller than 12 cm. The double punch wheel mechanism, the depth wheel and the covering wheel are the only moving parts of each drill unit.

Each drill unit works independently to execute its functions totally eliminating transmission systems like: sprocket and chain or pulley and belt. Obviously to synchronize the movement of drill units to control the pattern of seed distribution in an area a transmission system would be required.

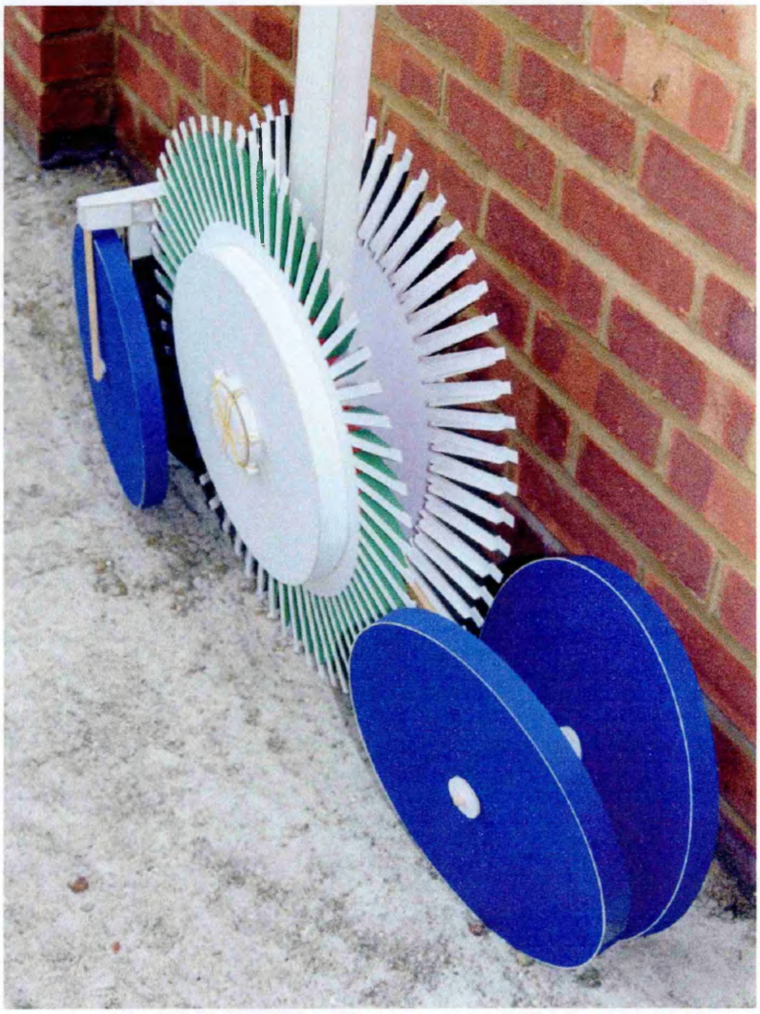


Plate 4.3.: Precision punch planter cardboard model

The final layout of the precision punch planter prototype and the shape of its components can be seen in detail in the next section.

4.4. Detailed design of a precision punch planter

The concept and the layout of the precision punch planter were further developed in the final design stage. Detailed manufacturing drawings were produced for all parts specifying materials and tolerances. Assembly drawings were made for the main systems. These drawings are shown in appendix A. A parts list is shown in the beginning of this appendix to facilitate the search for drawings.

Five assembly drawings are shown in the following section to describe the precision punch planter unit, the delivery punch wheel, the seed metering unit, the external punch wheel and the double punch wheel mechanism.

4.4.1. Precision punch planter unit

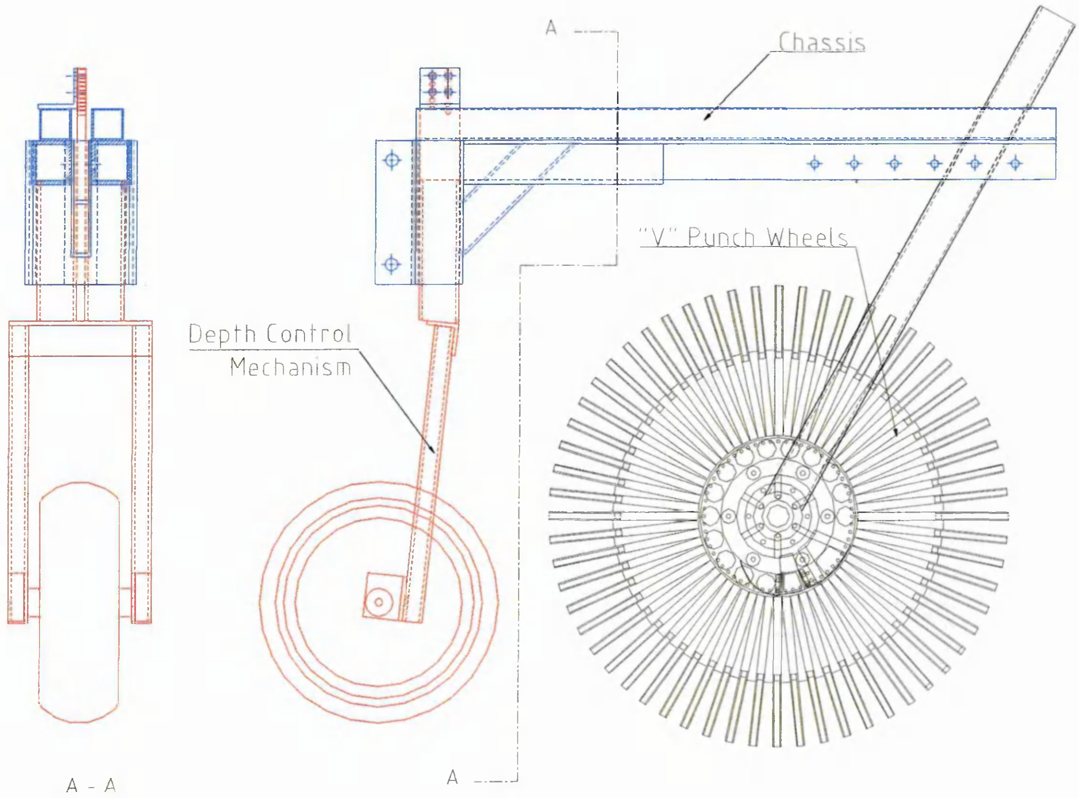


Figure 4.16: Precision punch planter unit

An assembly drawing of the precision punch planter prototype is shown in figure 4.16. It is a narrow unit that fits inside an envelope of 120x500x500 mm - width, length and height respectively. The drill is formed by two punch wheels, one depth wheel and a chassis. The external punch wheel is not shown on the drawing so that the seed metering mechanism can be seen. The seed box and the pressing wheel are also not included in this drawing.

The punch wheels which are placed in a "V" enclose almost all systems of the machine including the systems in charge of seed selection and delivery. Several complex functions are executed by these two moving sets of parts. The depth control mechanism uses a front wheel to control punch wheel working depth. Seed depth can be varied in steps of 5 mm. The chassis has a "L" shaped layout. The front part of the chassis connects to a parallelogram linkage that keeps the drill vertically orientated when following ground contours. The back of the chassis is connected to the vacuum shaft of the punch wheels using two M12 bolts. The angle between the radius at the punch touching point and the radius vertically orientated at the bottom of the wheel can be adjusted at this connection.

4.4.2. The delivery punch wheel

The delivery punch wheel (figure 4.17.) is a simple unit which performs complex functions. It is basically a narrow wheel with radial hollow punches which incorporates a seed metering unit at its centre and a seed delivery system on its periphery. The seed metering unit is operated by vacuum and the delivery system is powered by centripetal acceleration, gravity and air jet. Some components perform several functions therefore they belong to more than one system.

The punch wheel itself is formed by the delivery punches, a disc and a central shallow cylinder made of mild steel. The disc has an external diameter of 414 mm and a central hole of 212 mm. The central cylinder which is pressed into the disc hole has an external diameter of 212 mm, an internal diameter of 96mm and a height of 30 mm. This cylinder has a vacuum chamber in which a seed disc is attached. Sixty hollow punches for internal seed delivery are made using a box section of 20 x 10 mm with a 1.5 mm wall. They are 187 mm long and are radially fixed in the disc using M4 countersunk screws. The punch wheel disc is bolted onto the delivery hub using six M8 bolts. This hub transfers vacuum from the centre of the shaft to the vacuum chamber behind the seed disc. The central part of the disc and the delivery hub and are also parts of the seed metering unit.

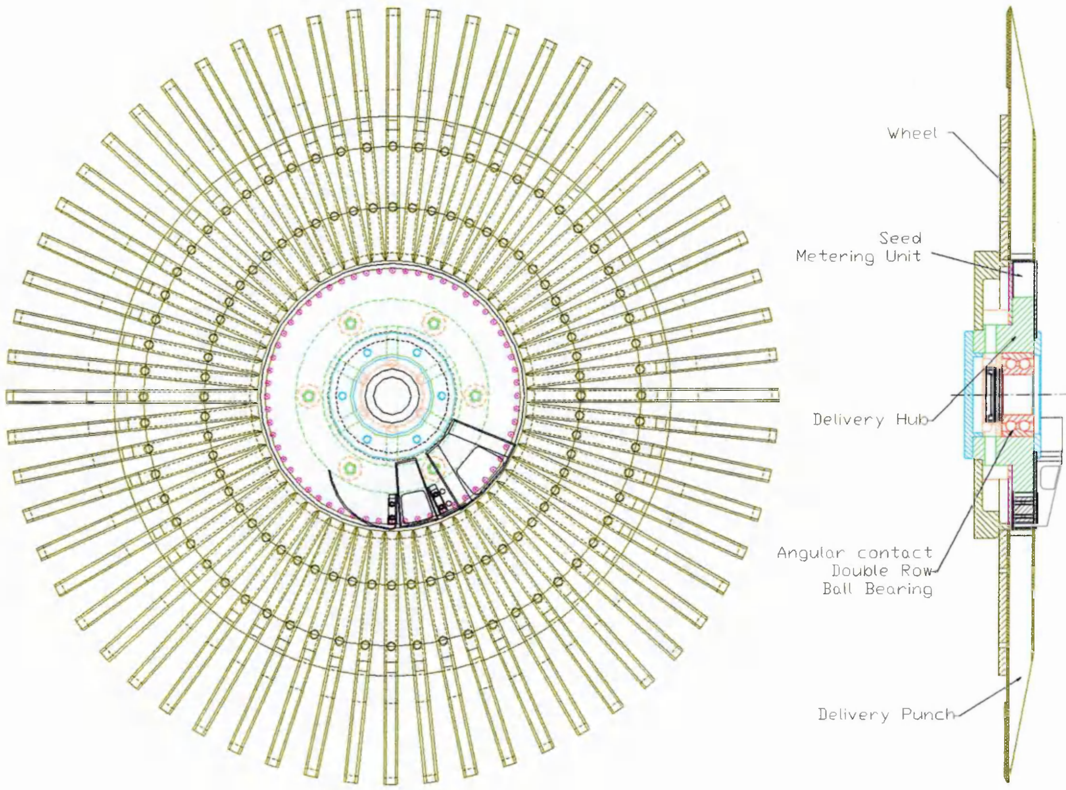


Figure 4.17: Delivery punch wheel with central seed metering unit.

4.4.3. The seed metering unit

The seed metering unit and its main components are shown in detail in figure 4.18. The flow of seeds can be easily visualised. Seeds enter the metering mechanism through the seed inlet port reaching a selection chamber. At the back of this chamber a seed disc rotates together with the punch wheel. The main seed disc has 60 holes in which air flows from the seed chamber into the vacuum chamber. Another seed disc with appropriate hole size is placed over the main seed disc. This disc may have 60, 30, 20, 15, 12 or 10 holes to adjust seed spacing. When vacuum is applied seeds are sucked and captured over these holes. Seeds then rotate with the disc to be individualised by the singulator and ejected by the seed ejector. At this point seed delivery starts. During operation, everything rotates at the same speed except the metering cover assembly which remains stationary. This part houses the seed ejector, seed singulator, seed inlet

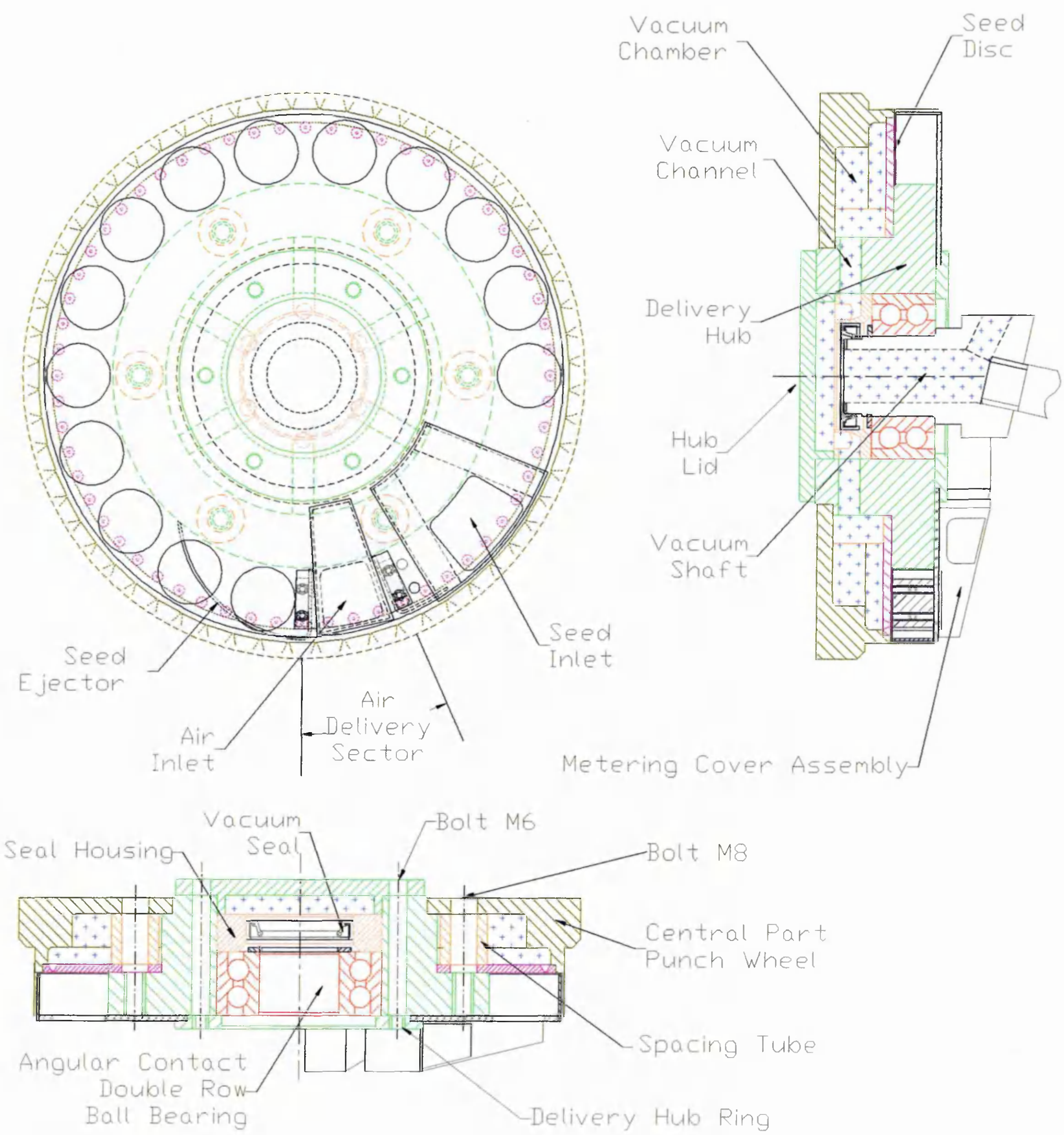


Figure 4.18: Seed metering unit – seed selection made by vacuum.

and air inlet. This cover has a radial opening near the ejector and in front of the air delivery chamber to allow seed transfer and air pressure application into the delivery punches.

Seed trajectory during delivery can be visualised in figure 4.17. After ejection seeds travel inside the delivery punches powered by air jet, centripetal force and gravity. The flow of air inside the delivery punches starts immediately after seed ejection. At this point the punch opening that had just received a seed becomes exposed to an air pressure chamber located behind the air inlet port. This chamber can be seen in figure 4.18. Only four punches at a time receive the air jet for seed delivery. After seed delivery a new cycle restarts when another seed selection is made.

The delivery hub to which the punch wheel is bolted can be seen in detail in figure 4.18. The hub and its auxiliary parts incorporate several vacuum channels to supply the seed metering unit with vacuum delivered by a hollow shaft. The delivery hub rotates around a hollow shaft using just one double-row angular-contact ball bearing. The bearing selected is a relatively new development that can replace two single row angular contact ball bearing mounted in tandem. Therefore it can support axial loads as well as radial loads by itself. The use of this bearing was fundamental to keep the hub compact, leaving more room for other systems like the seed meter. The use of a hollow shaft required a slightly tighter fit, with the bearing and close tolerance to guarantee a solid assembly.

4.4.4. The external punch wheel

Figure 4.19. shows the external punch wheel which is formed by a hub, a disc and 60 punches. An angular contact double row ball bearing is fixed inside the hub by two internal circlips. The hub is bolted in the disc using six M8 bolts and the punches are fixed in the disc using M4 countersunk screws.

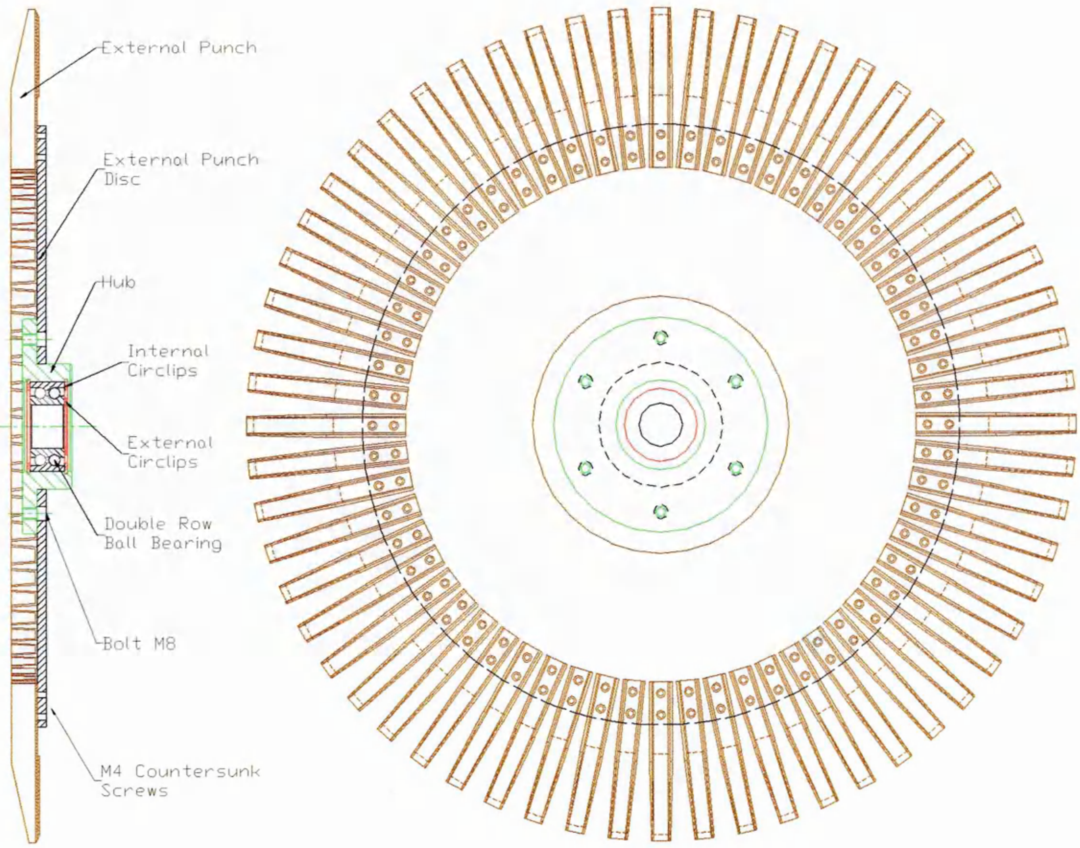


Figure 4.19: External punch wheel

4.4.5. The double punch wheel mechanism

The set of punch wheels arranged in a "V" is shown in figure 4.20. The delivery punch wheel and the seed metering unit is shown on the left and the external punch wheel is shown on the right. When access to the seed metering unit is needed the external punch wheel together with its shaft can be removed rapidly by detaching only one M16 bolt. Vacuum is transferred from the vertical arm into the seed metering unit using the hollow shaft on the left and several channels made in the seal housing and delivery hub. A vacuum seal is used to avoid lubricant suction from the ball bearing.

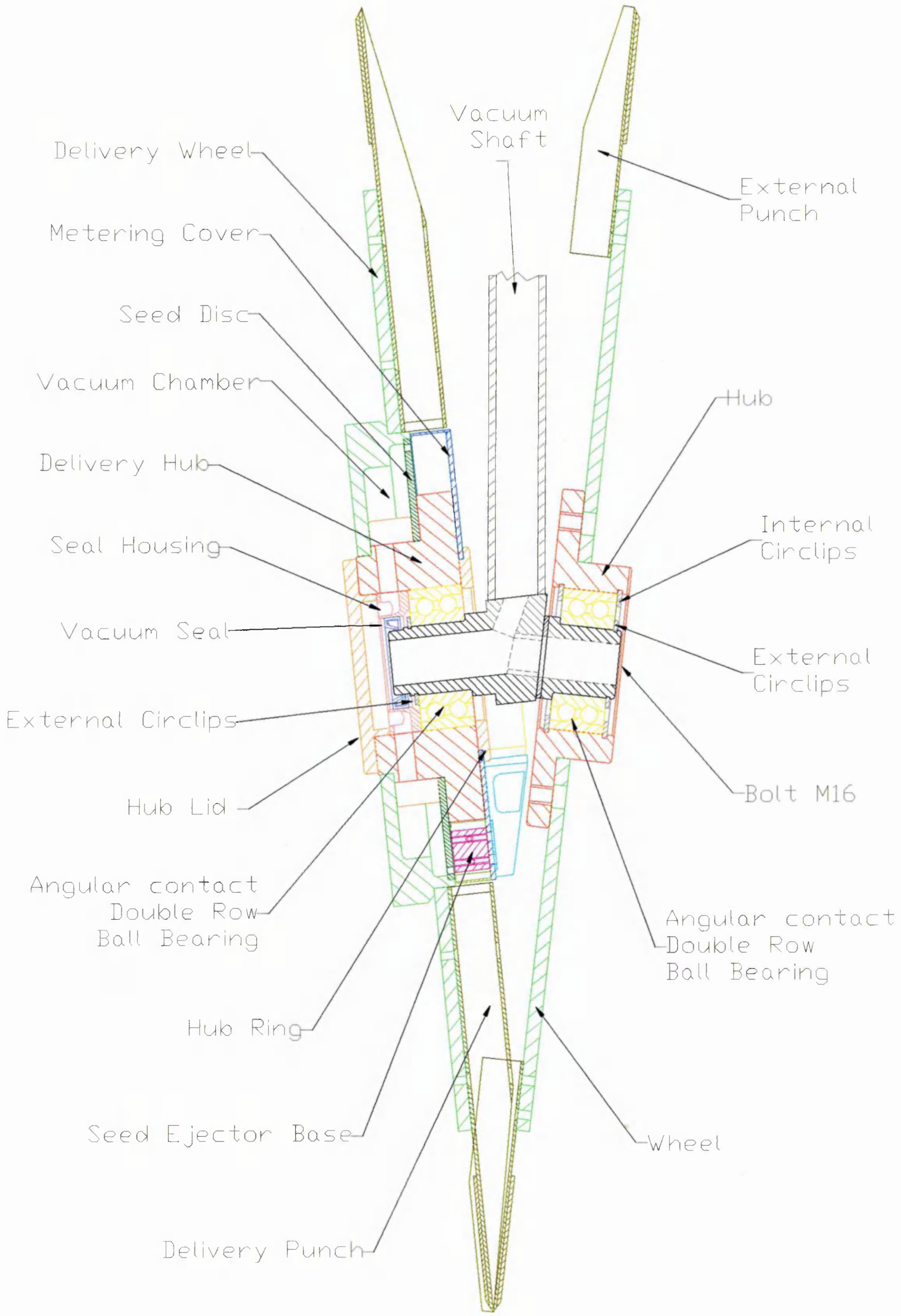


Figure 4.20: Punch wheels arranged in "V" with seed metering unit.

4.5. Precision punch planter prototype construction

The precision punch planter prototype (Plate 4.4.) was manufactured in the workshop at Cranfield University - Silsoe. The pair of punch wheels arranged in a "V" received a varnish coating after being cleaned. Note the opened punches on the right side of the punch wheels. The chassis is the top part of the unit to which the punch wheels arm is attached. It also connects to a parallelogram linkage to control vertical movement. The punch wheel arm is also used to transfer vacuum. The prototype is fitted with front and rear wheels connected by a horizontal bar. This bar is articulated with a vertical support to move the punch wheel up and down according to ground contours. The back wheel is also a covering/pressing wheel. These depth wheels and the parallelogram linkage were Stanhay Webb drill components. The press wheel on the back was moved laterally to show the back of the punch wheels more clearly. A GPS antenna also appears in the picture but was not used.

Plate 4.4: Precision punch planter prototype

A close up of the rolling components is shown in Plate 4.5. On the left side of the punch wheels it is possible to visualise how pairs of punches from distinct wheels get closer when the wheels rotate. The delivery punches get into the external punches to form a close surface (edge shaped) before entering the soil. As the wheel continues to rotate, opposite punches move away from each other to open a hole in the soil. The external punch wheel can be disassembled together with its hub, bearing and shaft by removing only one M16 nut. These punch wheels were originally designed with punch reinforcements welded to the external part of each punch but they were constructed without these reinforcements to save manufacturing time.

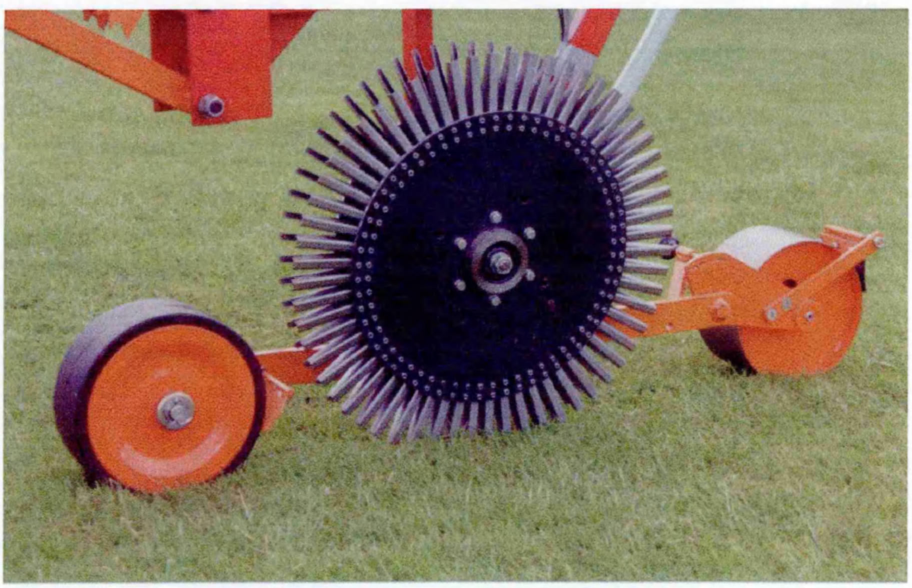


Plate 4.5: Close up of rolling components.

A picture of the prototype without the external wheel is shown in Plate 4.6. Internal components are displayed. The flexible hose on the right is the seed tube. The seed box is not installed. The hose on the left is the air pressure line that delivers a radial air jet immediately after seed ejection. The punch wheel's arm which is welded to the punch wheel's shaft is a structural component as well as a vacuum tube.

The seed metering cover in the central region of the punch wheel is used to fix the seed ejector, the seed singulator and wall chambers for seed selection, singulation, ejection and seed delivery using an air jet. While the machine is working this part remains immobile. It can be rotated to adjust seed ejection point properly to achieve precise seed delivery inside the hole in the soil. The air jet for seed delivery passes through the seed disc, therefore it helps to keep disc holes clean. After seed ejection an air jet is radially delivered to four punches at a time to propel seeds inside the punches. The air jet reduces seed delivery time and also helps to keep the delivery punches clean.

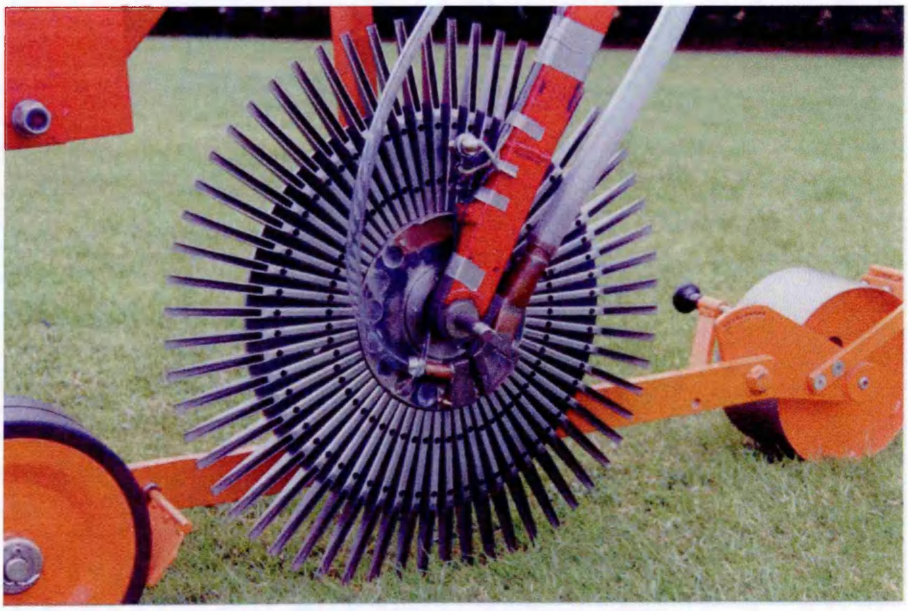


Plate 4.6.: Punch planter prototype without the external wheel displaying the delivery punch wheel and the seed metering unit.

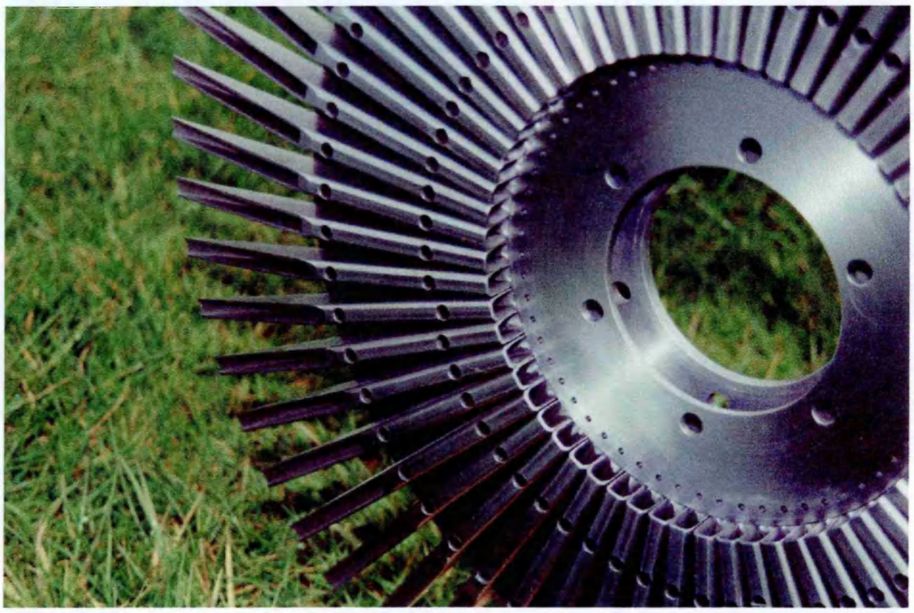


Plate 4.7. Delivery punch wheel with seed disc

The delivery punch wheel is shown in Plate 4.7. A seed disc of 60 holes is being used therefore it is possible to see that there is one hole for every punch. To change seed spacing this disc can be changed or a mask disc can be put over the main disc to cover some holes. This punch wheel is bolted on its hub using six M8 bolts and a set of 6 spacing tubes (which are not shown) that are put between these two discs. In this way the seed disc becomes part of the wheel structure to create a stiffer assembly. The region between the two central discs is the vacuum chamber. Air flows into the vacuum chamber passing through the sixty holes in the disc. The hollow punches have one end chamfered to make a funnel mouth for seed delivery. Vacuum is transferred from the hub to this chamber using six radial holes. The punches are radially fixed using M4 countersunk screws.

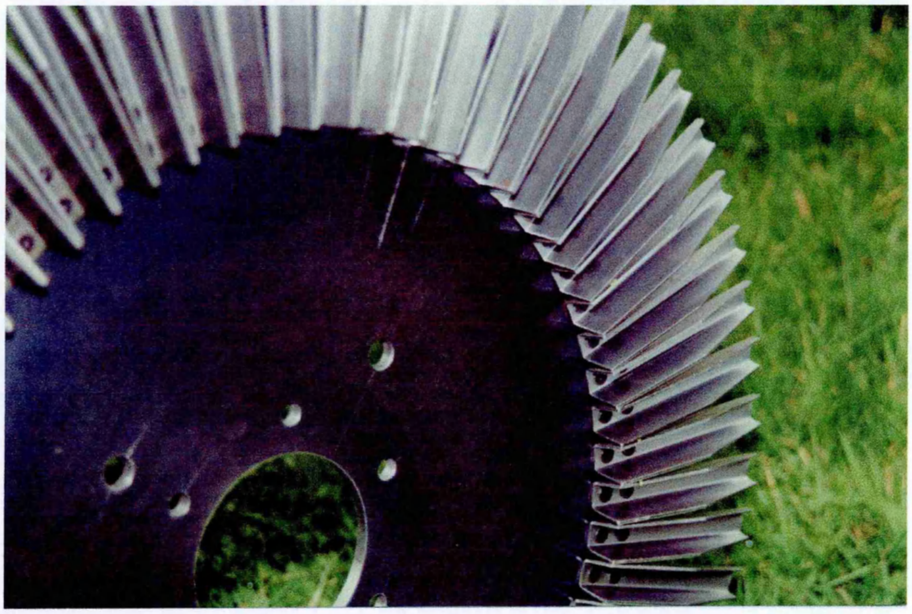


Plate 4.8: External punch wheel

The external punch wheel in shown in Plate 4.8. It is formed by one disc with sixty punches radially bolted to it. Two M4 countersunk screws are used to fix each punch. The disc is fixed on its hub using six bolts M8 (not shown in the picture).

5. Experiments

The precision punch planter prototype was evaluated in a soil bin to test its performance in relation to seed placement of pelleted sugar beet and wheat seeds at 4, 6 and 8 km/h. Seed spacing was set to 18 cm and seed depth to 3.0 cm. Seed dimensions are presented and the experimental design, infrastructure, the preliminary tests, the soil preparation, the punch planter set-up and finally the tests are described.

5.1. Wheat and pelleted sugar beet dimensions

A sample of 60 seeds for both, wheat and sugar beet, were taken to measure their main linear dimensions. The results are shown in Figure 5.1 for wheat and Figure 5.2 for pelleted sugar beet.

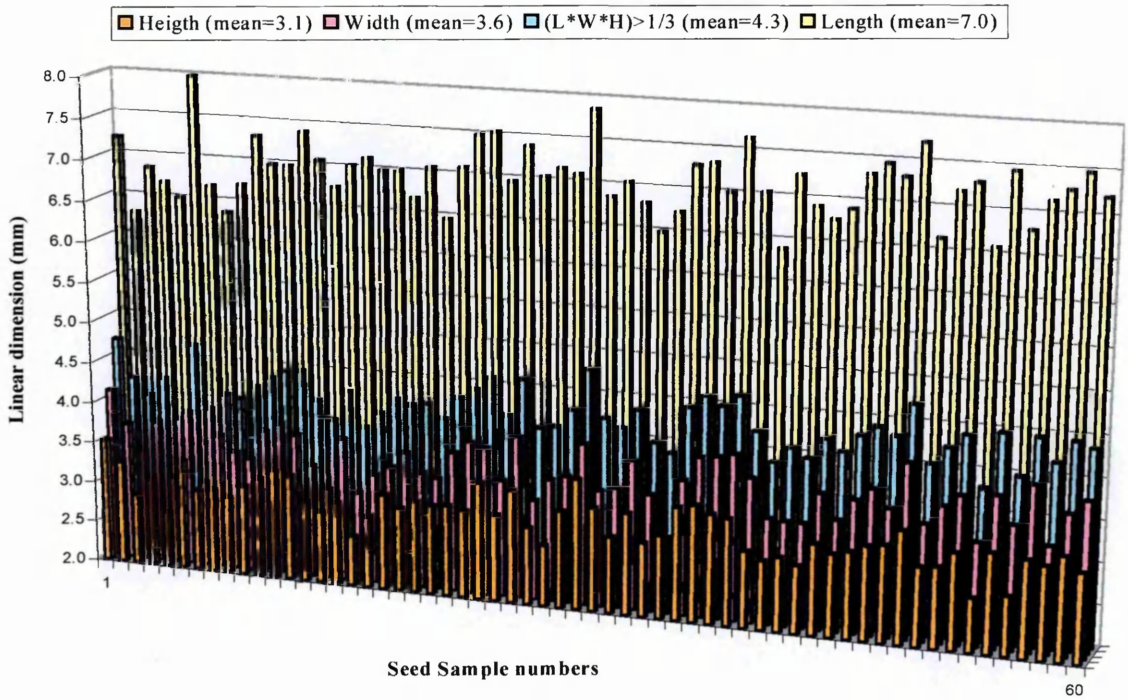


Figure 5.1. Main dimension of wheat seeds.

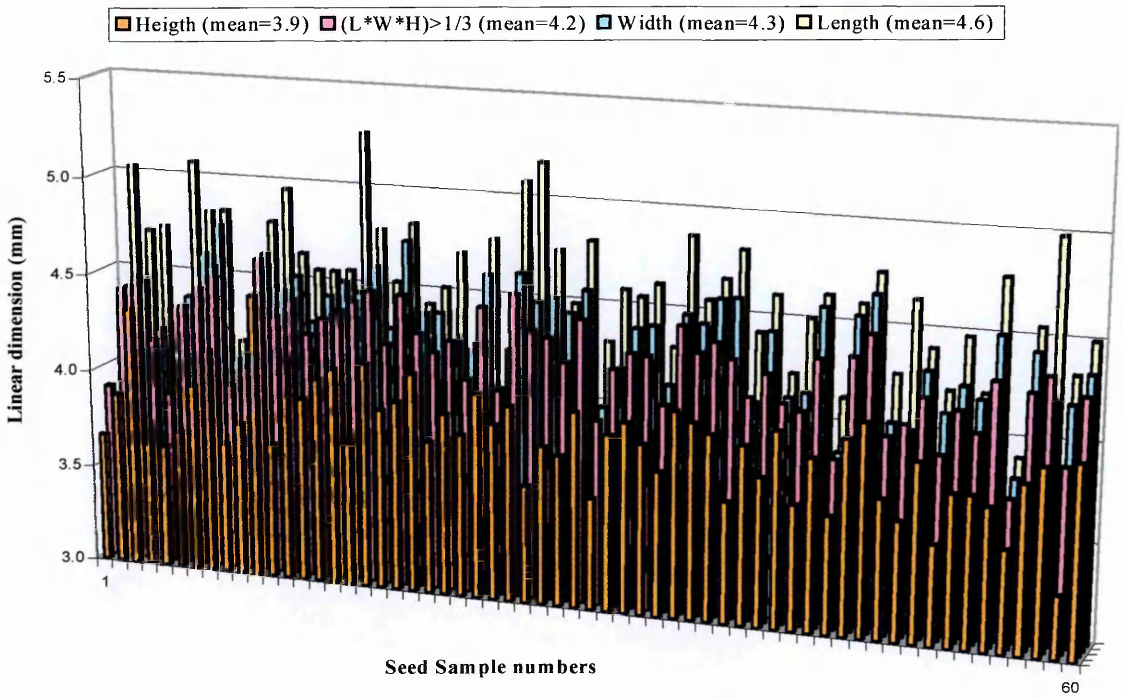


Figure 5.2. Main dimension of pelleted sugar beet seeds.

5.2. Experimental design

The experiments were done using a completely randomised block design. Each treatment consists of a combination of seed type and speed. The machine was tested for two seed types pelleted sugar beet and wheat, at three speeds 4, 6 and 8 km/h. Each treatment was replicated three times resulting in a total of 18 experiments. In all experiments the planter was adjusted to place seeds 18 cm apart at 3 cm depth. A sandy soil was used during the evaluation, soil classification is shown in appendix D.

5.3. Experimental infrastructure

The experiment environment utilised a soil bin with an electric winch to pull the machine along it. An electronic data acquisition system was used to measure the planter travel speed and distance.

The soil bin was protected from the elements by wood walls and a plastic roof. A trolley was used to guide the precision punch planter prototype along the soil bin. This trolley had two metallic wheels on one side of the soil bin and two pulleys on the other side. The wheels run over a metallic surface and the pulleys run over a guiding track. The drill prototype was fixed to this trolley using a parallelogram linkage to control vertical movements of the prototype. A platform fixed in this trolley served as support to a vacuum cleaner used as a vacuum source for the seed metering unit.

An electric winch was designed and built to pull the precision drill prototype along the soil bin (Plate 5.1). The winch was powered by an electronically controlled electric motor powered by two 12 volts batteries. The electronic control unit model DS100 was manufactured by Dynamic. A gear box, a pair of sprockets and a chain were used as transmission systems. The output shaft, where a drive pulley was attached, was mounted using a pair of self aligning ball bearings.

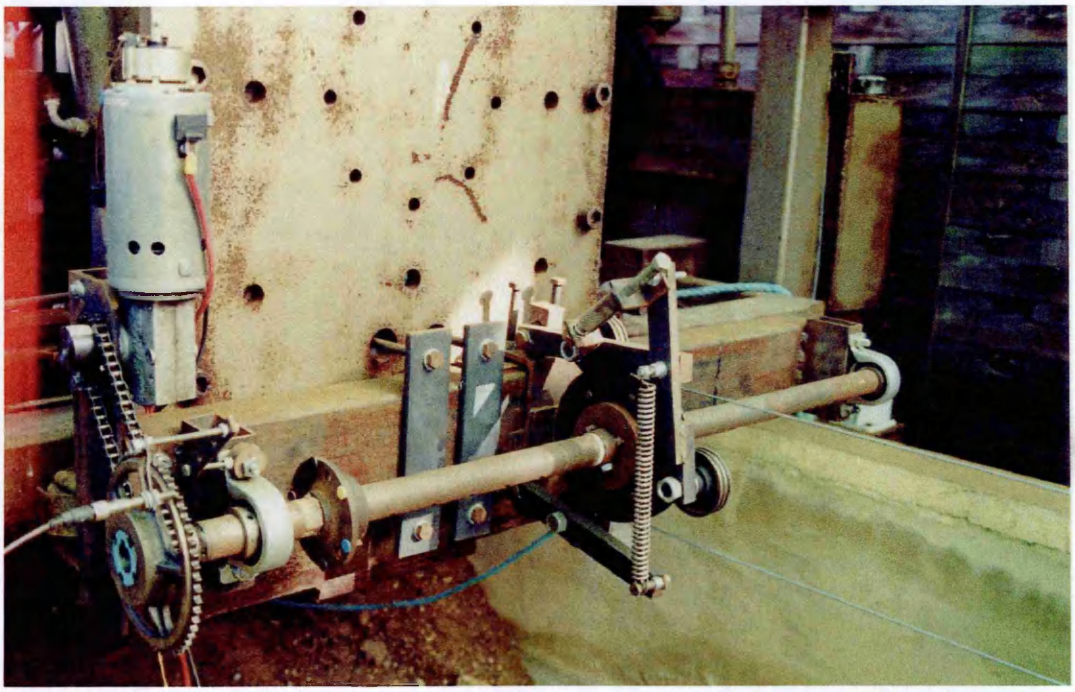


Plate 5.1. Electric winch developed for pulling the prototype along the soil bin

A wire rope formed a loop alongside the soil bin length. Both ends of the rope were fixed to the trolley using tensioning devices to vary the rope length. The Loop was supported by two pulleys with horizontal shafts, the winch's driving pulley and a tightening pulley. They were placed in opposite edges of the soil bin. Three loops of wire cable around the driving pulley were used to provide traction and a half loop around the tensioning pulley. The wire loops around the driving pulley were guided by three pulleys. The tensioning pulley was mounted in a sliding block which was pulled by a spring to tight the wire rope. The spring load could be adjusted by turning a M12 bolt.

A vacuum cleaner manufactured by Draper, model WDV 1100, power 1.1 kW was used as a vacuum source for the seed metering unit. This unit was operated at maximum power for all tests producing a vacuum of 0.026 bar. Seed air delivery was supplied by an air compressor with tank (50 litres) manufactured by Serbato, model 3500 IIX, power 18 kW. Air pressure was set to 6 bar.

To measure the planter speed during the tests an electronic measuring system using a microcomputer was developed. It used an inductive sensor installed in the winch that detected rotation movement of a sprocket. The signal generated by this sensor was input into a data acquisition board connected to a microcomputer through a parallel port. Dasylab software was used to collect and record this measurement. The travel speed was indicated using an analogue display and the travel distance was indicated by a digital display. The system was calibrated by pulling the prototype 12 metres along the soil bin eleven times. The measurement of the electronic system was compared against the measurement of a measuring tape placed alongside the trolley track. The mean error was –6 mm and the standard error was 9 mm. The maximum and minimum errors were 10 mm and –18 mm respectively.

The precision punch planter prototype, ready to test, is shown in Plate 5.2. The punch planter was attached to the trolley, which is pulled by the lower part of the wire loop shown in the middle of the soil bin. The tensioning pulley was fixed to the end wall shown in the picture. The vacuum cleaner, which supplied the seed metering unit, is shown on the top left corner.

Plate 5.2. Precision punch planter prototype ready to test

5.4. Preliminary tests and preparations for the experiments

Seed discs were selected and the precision punch planter prototype was fine tuned for the subsequent evaluation in the soil bin.

5.4.1. Determining the hole size for the wheat seed disc

The shape and size of wheat seeds make seed selection a difficult task even for a vacuum operated seed metering unit. As wheat is generally drilled at high rates, the prototype must make 74 seed selections per second when the planter travels at 8 km/h drilling seeds 3 cm apart (the smallest possible setting for seed spacing).

The prototype was designed to use mask seed discs to be put over the main seed disc. The main seed disc was made with steel and the mask discs were made with plastic (Poly Ethylene Terephthalate). To determine the appropriate hole size for the wheat seed disc some preliminary tests were conducted. During these tests four mask seed discs with 1.2, 1.4, 1.6 and 1.8 mm hole diameters were tested. The seed metering unit was supplied with a vacuum of 0.026 bar and the delivery punch wheel was rotated using a variable speed hand drill and a shaft with a rubber wheel. The seed disc with 1.8 mm diameter holes was easily torn because the pointed end of wheat seeds were being excessively sucked into the holes and the seed disc holes were damaged during seed ejection. When using the seed disc with 1.6 mm diameter holes, seeds were sometimes selected by its pointing end but seed penetration was not enough to damage the disc holes during seed ejection. The discs with 1.2 mm holes in diameter rarely selected seeds and the discs with 1.4 mm holes in diameter also had a poor performance. The seed disc with 1.6 mm holes was therefore selected for the experiments in the soil bin.

5.4.2. Determining the hole size for the sugar beet seed disc

Selecting pelleted sugar beet seeds is easier than selecting wheat seeds due to the extreme difference in shape between these two seeds. The spherical shape of the pelleted seeds perfectly match the seed disc holes creating a circular interface. This interface works as an efficient seal against air leaks improving seed selection by suction.

For pelleted sugar beet seeds a hole size of 2.2 mm was selected. This selection was based on the Amazone ED 601 – K tronic contour precision seed drill, which was evaluated for pelleted sugar beet seeds (Profi International No5 2001). During this evaluation a disc with 2.2 mm holes was used and the seed metering unit had an exceptional performance. Based on this information, the same hole size for the seed disc was then selected for the prototype. The sugar beet seed disc with 2.2 mm holes had a very good performance during the preliminary tests and did not get torn.

5.4.3. Adjusting the seed release point

The faster the planter travels the earlier the seeds need to be released from the metering unit. The seeds need to reach the punch tip before the punch starts to leave the soil. In other words, the seeds need to be placed in the soil at the lowest point that the punch penetrates the soil to guarantee precise seed spacing and depth.

To adjust the release point the seed metering cover is turned changing the seed ejector position. The relative positions of the seed inlet, the seed singulator, and the air outlet (for seed delivery) are automatically adjusted because they are all fixed in the metering cover. In this way all different functions are timed simultaneously using a very simple mechanism. Once the seed releasing point is set the metering cover is fixed.

Some preliminary tests were conducted to determine the correct set-up for seed releasing points for 4, 6 and 8 km/h. During these tests the planter was kept stationary and the punch wheels were positioned approximately 5 cm above the soil. Vacuum and air pressure were applied. The punch wheels were then rotated at the desired speed using a hand drill with a shaft and rubber wheel as a drive mechanism. The speed was measured using an electronic speedometer that was previously calibrated for the punch wheel diameter. The seed release mechanism was then adjusted for each speed (4, 6 and 8 km/h) to make the planter deliver seeds at the lowest point of the punch wheel. These settings were used for all the subsequent tests.

5.5. Soil preparation

The soil was prepared by hand before each experiment. A strip of soil where the machine would be tested was removed to another place where water or dry soil were added and the soil was mixed to homogenise it before being put back in the soil bin. This measure was necessary to achieve similar moisture contents for all of the experiments. At this point a soil ball was made by hand and then pressed giving a feeling of the moisture available. After the soil was returned it was pressed using a hand operated roller. Immediately before the runs three soil samples were collected from alongside the soil bin (Plate 5.3) to have their bulk density and moisture content analysed in the lab. The bulk density varied from 1300 to 1550 mg/m^3 and the moisture content varied from 3.0% to 4.5 %

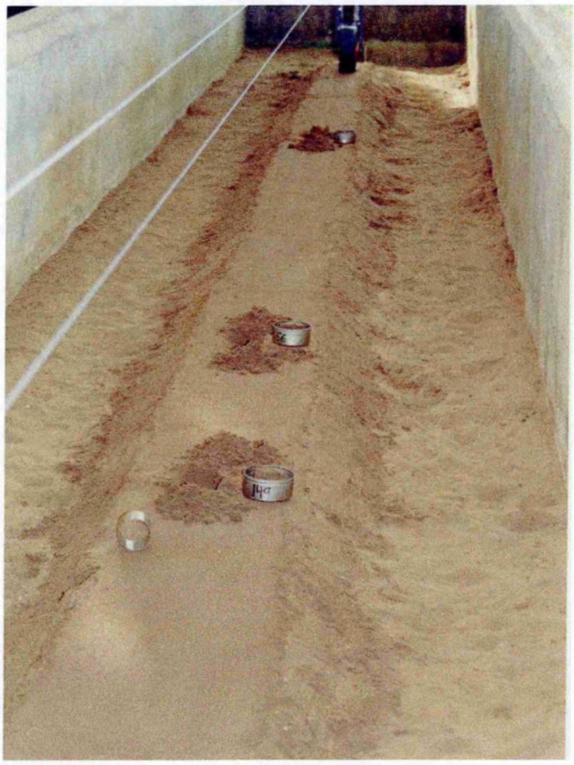


Plate 5.3. Soil sampling to determine bulk density and moisture content

5.6. Punch planter set-up

The machine was prepared for the experiment by fitting the seed disc, loading the seeds and adjusting the seed releasing point for the speed to be tested. The depth wheel was adjusted for 3 cm. No cover wheel or other device to cover or press the soil after seed delivery was used. Rarely could a seed be seen after the tests because the hole walls partially collapsed after the punches left the soil. A cover wheel had been previously tried but was abandoned to facilitate seed location in the soil.

5.7. Test procedure

The vacuum cleaner and the compressor were turned on. The compressor had its air tank charged. The air tap was opened at the same position it had been opened during calibration of seed releasing point (2 full turns). The machine was then pulled by the winch. During the first metre the machine was also pushed by hand to accelerate it up to the required speed. During the test the travel speed and distance were measured and indicated on a computer screen using Dasylab. An operator controlled the speed by turning a knob in the control box. Plate 5.4 shows a test being conducted. During the experiments at 4 km/h, the speed varied from 3.5 to 6.0 km/h, at 6 km/h it varied from 5.5 to 7.2 km/h, and at 8 km/h it varied from 7.0 to 10.1 km/h.

Plate 5.4 Prototype being tested

5.8. Measurement of seed positions and depths

After pulling the machine the most arduous task started, the search for seeds in the soil and the measurement of their positions. A measuring tape was placed in parallel with the drilled row starting from the point where the machine was resting before the test and stepped at the point it finished. The soil was excavated to reveal the seeds without moving them from their resting place. Seed position measurements in relation to one reference point (where the machine started its movement) of all drilled seeds were made. Seed depth was measured using a sliding rule in a square device that was placed over the soil surface (Plate 5.5). The measurements made during acceleration at the beginning and deceleration at the end of the drilled row were eliminated.

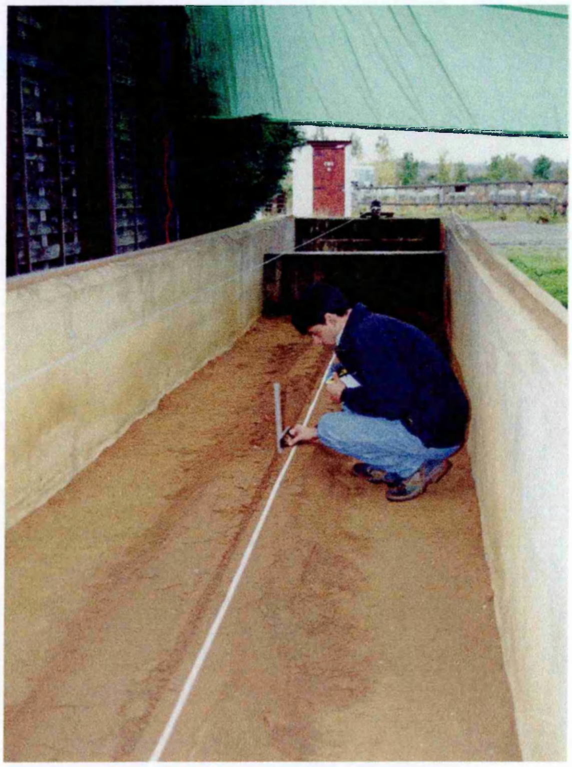


Plate 5.5 Measuring seed position and depth

An electronic measurement system was investigated to automatically measure seed position in the soil while the machine was being tested but it proved to be inaccurate. The data logger available could not count the number of events fast enough to obtain a reasonable accuracy. For 8 km/h this system was giving an error of 2.2 cm on punch position. Also investigated was the possibility of using the measurement system developed to measure the planter speed but when the extra sensors were connected to this system its acquisition rate had to be reduced to cope with a higher number of channels.

6. Experiment results

The experiment results consist of seed spacing histograms and eight measures of accuracy that are based on seed depth and seed position measurements.

Seed spacing histograms are the “fingerprints” left in the soil by the precision drill and show graphically the accuracy of the machine. These histograms are very helpful to understand and visualise the measures of accuracy obtained and will therefore be the first results presented.

The eight measures of accuracy calculated to evaluate the performance of the prototype are: mean seed depth, mean seed spacing, mean seed spacing within the target range, coefficient of precision – CP3, quality of feed index – A, missing index – M, multiple index – D and precision – C.

6.1. Seed spacing histograms

The seed spacing histograms for wheat and sugar beet seeds for 4, 6 and 8 km/h are shown in Figures 6.1. to 6.4. It was used intervals of 10 and 2 mm Seed spacing is represented on the x axis and frequency of spacing on the y axis. Ideally these histograms should have just one bar indicating 100% at 18 cm, which is the target seed spacing. However this ideal histogram is reduced due to double seeds, missing seeds and incorrect deliveries around the target spacing.

6.1.1. Seed spacing histograms for wheat

Figures 6.1 and 6.2 show seed spacing histograms for wheat using seed spacing intervals of 10 and 2 mm respectively.

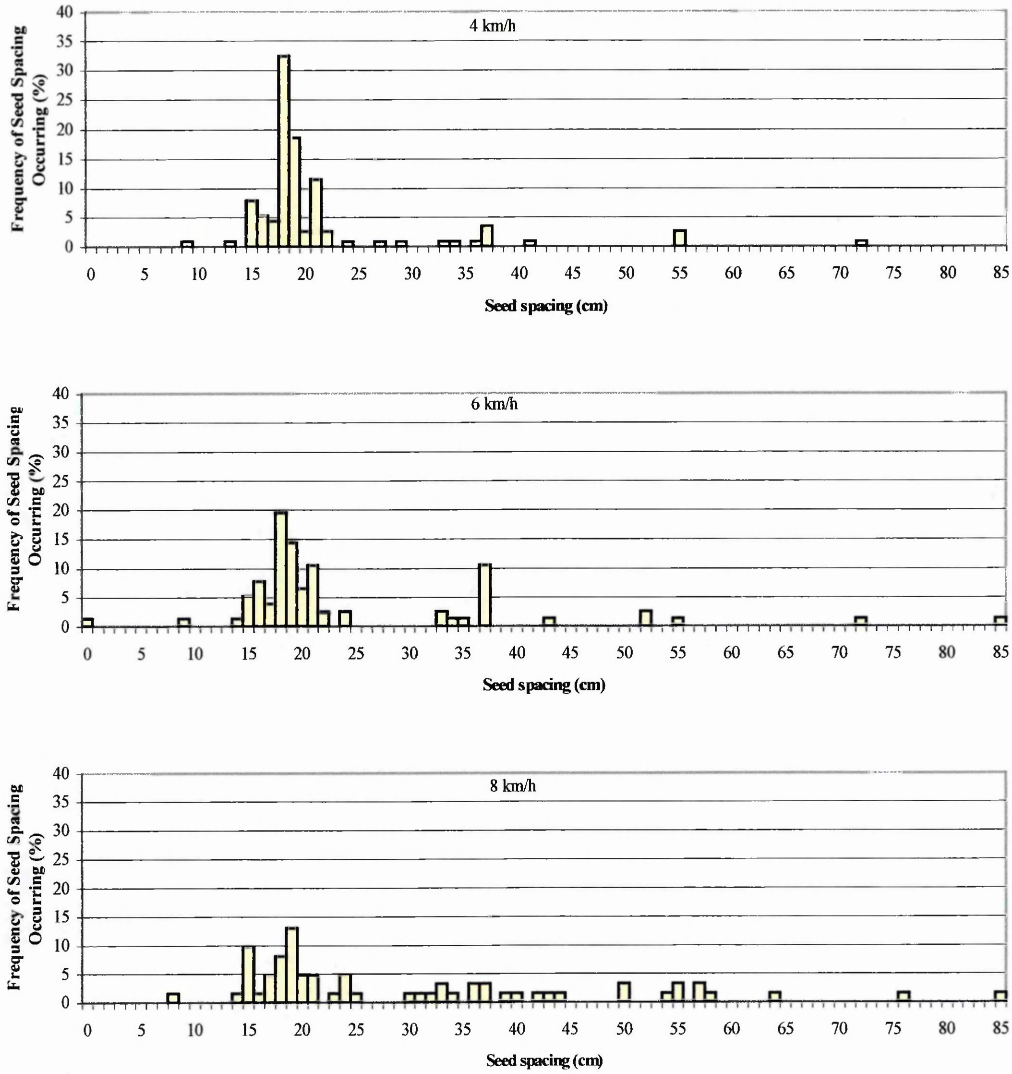


Figure 6.1: Seed spacing histograms for wheat seeds. Target seed spacing : 18 cm. Seed spacing intervals: 10 mm.

The general performance of the prototype for wheat seeds across a wide seed spacing spectrum is shown in Figure 6.1. It was used a seed spacing interval of 10 mm covering the whole seed spacing spectrum, which varies from 0 to 85 cm. The performance of the prototype for wheat for 4 km/h was very accurate. Note the large cluster of seed spacing around the target spacing of 18 cm where 32% of seed spacing produced was within the 18.0 to 18.9 cm range. When speed increased to 6 and 8 km/h this cluster was dramatically reduced indicating performance deterioration. The smaller clusters around 36, 54 and 72 cm indicate single, double and triple missing seeds respectively.

As speed increased the number of missing wheat seeds increased dramatically. The small number of observations around 0 cm shows that double seed selections were very rare for all three speeds tested.

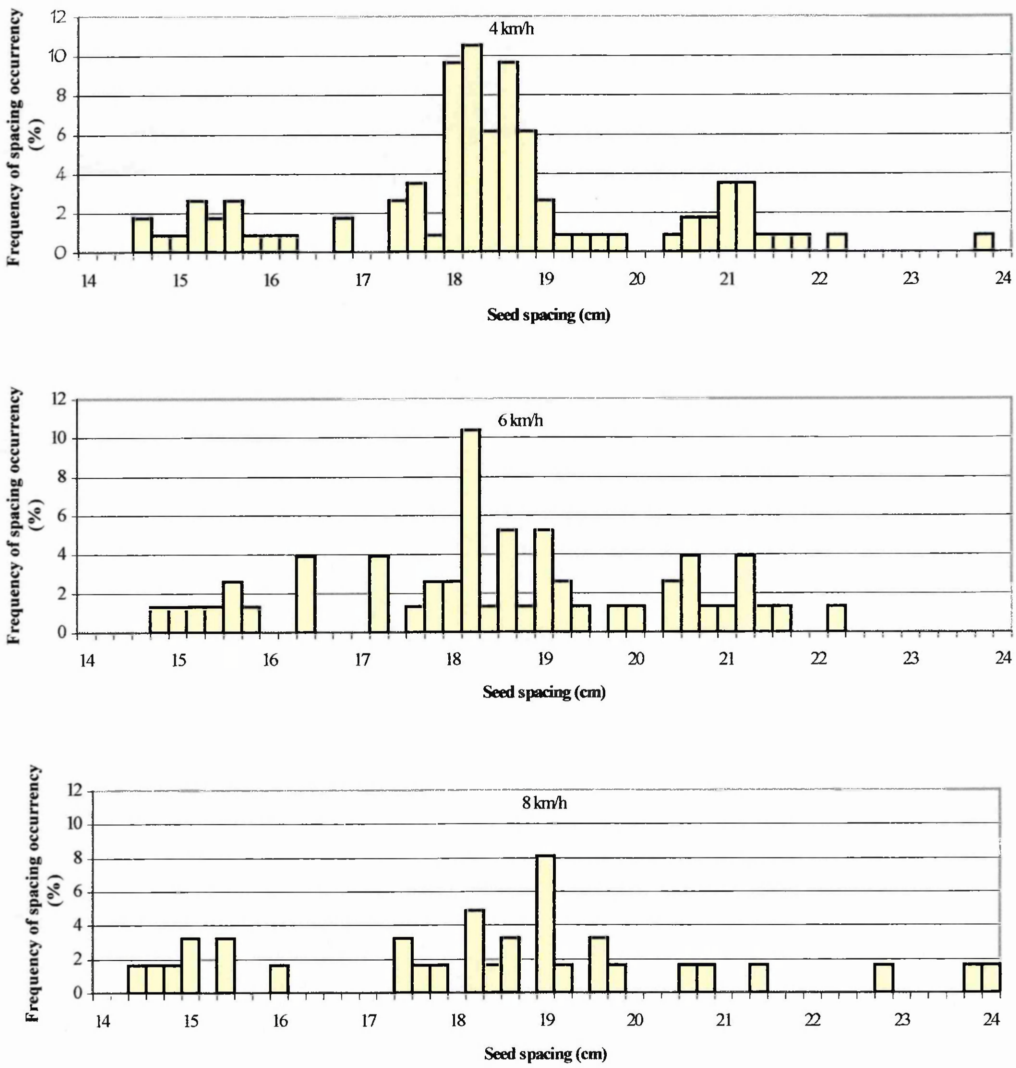


Figure 6.2: Seed spacing histograms for wheat seeds. Target seed spacing: 18 cm. Seed spacing intervals: 2 mm.

The seed spacing spectrum around the target seed spacing (ranging from 14 to 24 cm) is shown in more detail in Figure 6.2, where a resolution of 2 mm was used. These histograms illustrate the performance of the machine in relation to seed delivery independently from seed selection because missing and double seeds are not considered.

Note that for 4 km/h seed spacing distribution was concentrated around 18.0 to 19.0 cm range, but it is also possible to distinguish that the cluster around the target spacing is actually formed by three clusters. This pattern occurred for all three speeds. There is one larger cluster in the middle and two smaller clusters symmetrically placed around the main cluster. These two clusters are placed at the target spacing ± 3 cm (the seed spacing increment. They are clearly detached from the main cluster and are placed around 15 and 21 cm. Therefore they represent errors on seed placement caused by seed deliveries into wrong punches. Consequently, every time that a seed was delivered to a wrong punch two incorrect seed spaces were created, one smaller and another larger than the target seed spacing of 18 cm. These wrong deliveries were visually observed through the seed metering window while preparing the precision drill prototype for testing. The exceptional performance at 4 km/h can be clearly seen in this figure where 44% of the seed spacing produced were between 18 and 19 cm. At 4 and 6 km/h more than 10% of the seed spacing produced was equal to 18.2 cm.

6.1.2. Seed spacing histograms for sugar beet

Figures 6.3 and 6.4 show seed spacing histograms for pelleted sugar beet seeds. Figure 6.3 shows the whole seed spacing spectrum using seed spacing intervals of 10 mm. The performance of the prototype for pelleted sugar beet seeds was much better than for wheat seeds. There was a large cluster of seed spacing around the target spacing of 18 cm for all speeds. The number of missing seeds were much smaller for sugar beet than for wheat but there were smaller clusters around 36 cm and 54 cm indicating single and double missing seeds respectively. Seed selection slightly deteriorates when speed increased due to single missing seeds. The number of double missing seeds were rare and did not increase with speed. The small number of observations around 0 cm shows that double seed selections were very rare for all three speeds as it was for wheat seeds. The precision punch planter prototype had an remarkable performance at 8 km/h for sugar beet when 35% of the seed spacing produced was within 18.0 and 18.9 cm.

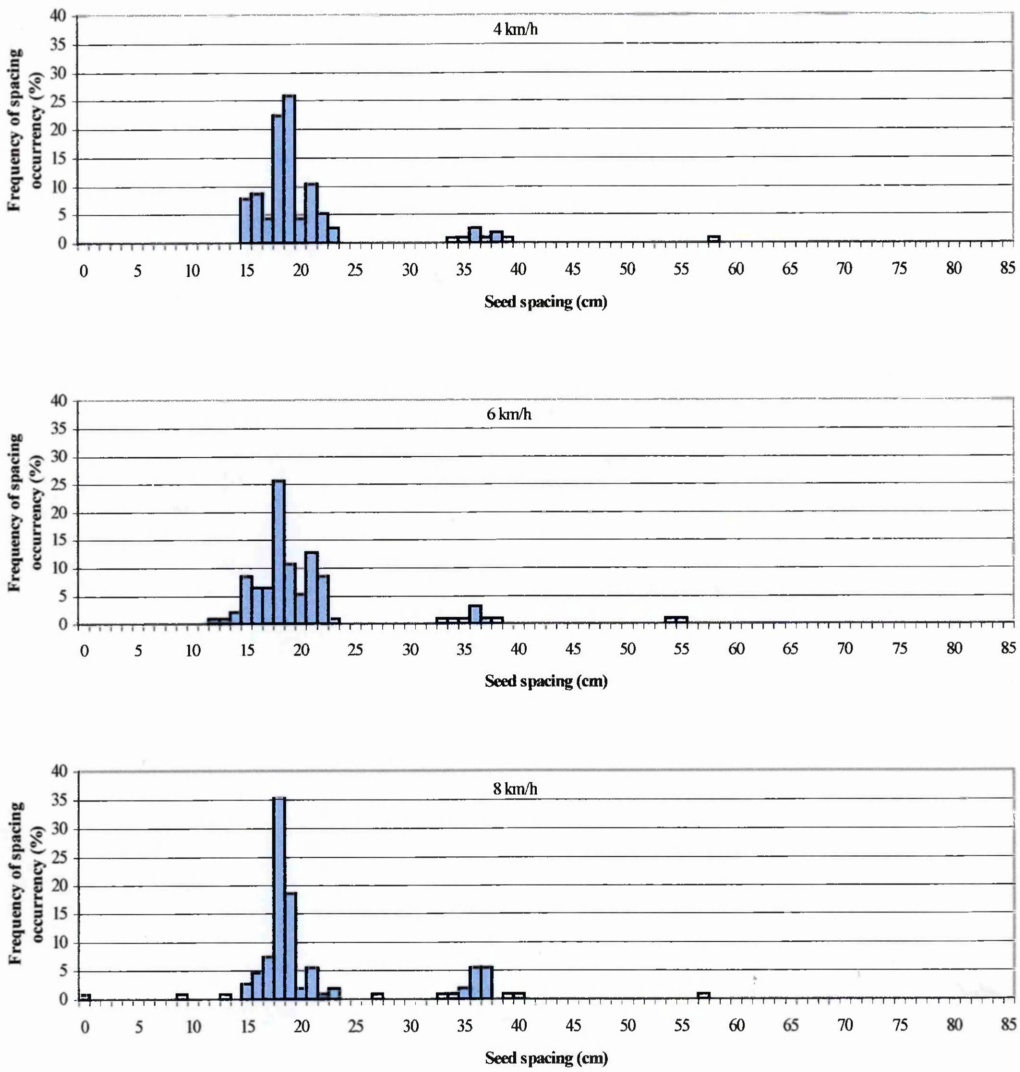


Figure 6.3: Seed spacing histograms for pelleted sugar beet seeds. Target seed spacing: 18 cm. Seed spacing intervals: 10 mm.

The seed spacing spectrum around the target seed spacing was explored in more detail in Figure 6.4, where a seed spacing interval of 2 mm and a seed spacing spectrum that ranges from 14 to 24 cm were used. The three clusters around the target spacing are clearly defined. The two symmetrical clusters slightly increased when the speed was increased from 4 to 6 km/h but they were significantly reduced when the speed increased from 6 to 8 km/h. This is an interesting result because it indicates that, for sugar beet, seed ejection and transfer into the delivery punches were more efficient for the higher speed tested (8 km/h). Most of the seed spacing produced, around the target spacing, was within the 17.0 to 19.9 cm range for all speeds tested.

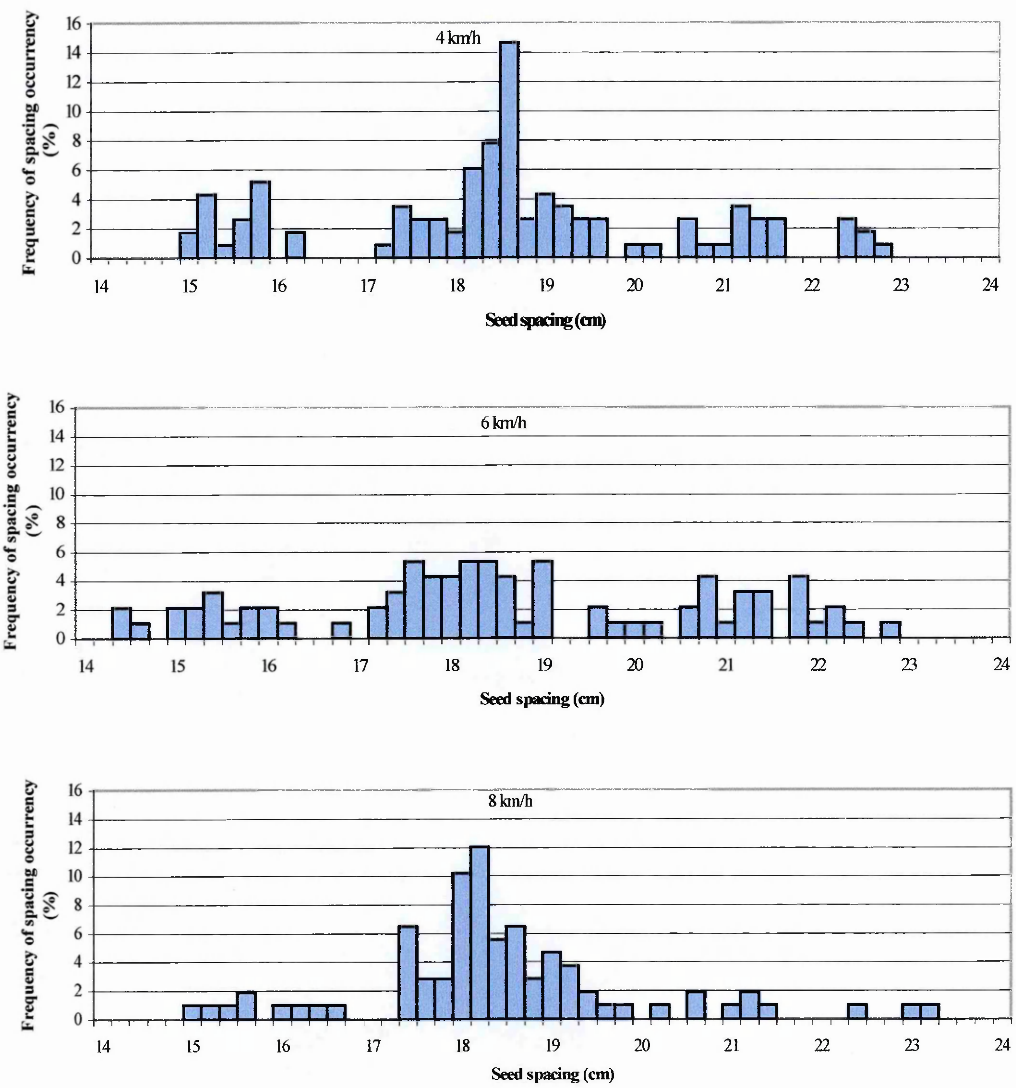


Figure 6.4: Seed spacing histograms for pelleted sugar beet seeds.

Target seed spacing: 18 cm.. Resolution: 2 mm.

6.2. Mean seed depth

The mean seed depth and standard error for both seeds for 4, 6 and 8 km/h are shown in Table 6.1 and Figure 6.5.

Table 6.1: Seed depth means and standard errors for seed and speed

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (mm)	SE (mm)	Prediction (mm)	SE (mm)
4	30.7	0.38	29.1	0.38
6	30.7	0.42	29.4	0.47
8	30.2	0.39	28.2	0.52

To investigate the influence of seed type and speed on seed depth, an analysis of variance (ANOVA) in randomised blocks was accomplished for seed depth, using the GenStat software. It was used an unbalanced design because the number of measurements varied for seed and speed. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There was no significant difference in seed depth means for speed (P=0.354).
- There was a very highly significant difference in seed depth means for seed (P<0.001).
- There was no significant difference in seed depth means for speed and seed (P=0.734).

The residual degrees of freedom was 563.

The results show a strong evidence that speed did not affect the punch planter's ability to produce uniform seed depth for both seeds. There was very small variation in the seed depth means for each seed when comparing speeds. The standard error was very small as was the case for all tests.

The mean seed depth and standard error for both seeds are shown in Table 6.2. The mean seed depth for wheat was 1.5 mm smaller than for sugar beat. This difference was highly significant statistically but is less important in practical terms. This difference could be due to seed shape affecting depth measurements and probably seed spacing measurements as well. The coefficient of variation and standard error of a single unit was 13.68 % and 4.08 mm respectively.

Table .6.2: Seed depth means and standard errors for seed type

Seed			
Sugar beet		**Wheat**	
Prediction (mm)	SE (mm)	Prediction (mm)	SE (mm)
30.55	0.23	28.92	0.26

Pelleted sugar beet seeds have a ball shape being symmetric in all directions. Wheat seeds have an elongated shape with different dimensions in length, width and height. While measuring seed depth (and also seed spacing) the reference point chosen was the centre of the seed. For wheat these measurement are dependent on seed orientation and for sugar beet it is independent.

Seed depth dispersion (or lack of it) is more important than mean seed depth. The later can be easily adjusted accordingly to requirements changing the set-up for the depth wheel. The low standard error values show that the punch planter produced uniform seed depth in all tests.

6.3. Mean seed spacing

The mean seed spacing and standard error for sugar beet and wheat for 4, 6 and 8 km/h are shown in Table 6.3 and Figure 6.5. Table 6.4 shows LSD for comparison between seed and speed. The mean seed spacing were always greater than the target seed spacing

Table 6.3: Seed spacing means and standard errors

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (cm)	SE (cm)	Prediction (cm)	SE (cm)
4	20.3	1.02	21.1	1.03
6	20.5	1.14	24.7	1.26
8	21.6	1.06	30.9	1.40

of 18 cm because it was influenced by the missing seeds. When a seed was not selected by the metering unit a large seed spacing was produced by the planter increasing the mean. This effect was much more prominent for wheat than for sugar beet.

Table 6.4: Least significant differences (at 5.0%) for predicted means of seed spacing

Speed Seed	**4 km/h Sugar beet**	**4 km/h Wheat**	**6 km/h Sugar beet**	**6 km/h Wheat**	**8 km/h Sugar beet**	**8 km/h Wheat**
4 Km/h Sugar beet	*					
4 Km/h Wheat	2.854	*				
6 Km/h Sugar beet	3.006	3.019	*			
6 Km/h Wheat	3.187	3.195	3.326	*		
8 Km/h Sugar beet	2.894	2.906	3.056	3.231	*	
8 Km/h Wheat	3.404	3.415	3.545	3.694	3.448	*

To investigate the influence of seed type and speed on seed spacing, an ANOVA (in randomised blocks) was accomplished for seed spacing, using the GenStat software. It was used an unbalanced design because the number of measurements varied for seed and speed. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There was a very highly significant difference in seed spacing means for speed ($P<0.001$)
- There was a very highly significant difference in seed spacing means for seed ($P<0.001$)
- There was a highly significant difference in seed spacing means for speed and seed ($P=0.001$)

The residual degrees of freedom was 563.

The results show a very strong evidence that speed and seed affected the mean seed spacing.

6.3.1. Comparison of mean seed spacing between speeds for sugar beet

The results show no significant difference (5% level) in the seed spacing means for all speeds tested (4 to 8 km/h) for sugar beet. The standard error was practically the same for 4 and 8 km/h and slightly bigger for 6 km/h. There is strong evidence that speed had no effect on mean seed spacing for sugar beet seeds.

6.3.2. Comparison of mean seed spacing between speeds for wheat

The results show a significant difference (5% level) in the seed spacing means between all speeds tested. The mean seed spacing for wheat increased significantly with speed. The standard error also increased with speed. There was a 40% increase on the standard error when the speed increased from 4 to 8 km/h.

6.3.3. Comparison of mean seed spacing between seeds for speed

The results show no significant difference (5% level) in the mean seed spacing for sugar beet and wheat when the planter was tested at 4 km/h. But for 6 and 8 km/h the results show a significant difference (5% level) in the mean seed spacing for sugar beet and wheat.

6.4. Mean seed spacing within the target range

This analysis was carried out to find out how the planter placed seeds in the soil when a proper seed selection had been done. Faults caused by the seed metering unit - double and missing seeds - were eliminated in this analysis. The mean seed spacing for sugar beet and wheat for seeds within the target spacing are shown in Table 6.5 and Figure 6.5.

Table 6.5: Seed spacing (within the target) means and standard errors.

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (cm)	SE (cm)	Prediction (cm)	SE (cm)
4	18.6	0.21	18.3	0.22
6	18.4	0.24	18.6	0.29
8	18.2	0.23	18.7	0.37

To investigate the influence of seed type and speed on seed spacing within the target range, an ANOVA in randomised blocks was accomplished for seed spacing within the target range, using the GenStat software. It was also used an unbalanced design because the number of measurements varied for seed and speed. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There was no significant difference in seed spacing means for speed (P= 0.919)
- There was no significant difference in seed spacing means for seed (P=0.771)
- There was no significant difference in seed spacing means for speed and seed (P=0.313)

The residual degrees of freedom was 462.

The results show no significant difference between seed spacing (within the target range) means for both seeds for all speeds tested. The mean seed spacing for sugar beet and wheat were very close to the target seed spacing of 18 cm, when double and missing seeds were eliminated from the analysis. More important than that, the results show that an uniform seed spacing was produced for both seeds for all speeds tested when the metering unit had successfully selected a seed. The mean seed spacing within the target region was constantly bigger than 18 cm the target spacing due to punch wheel slippage. However it remained relatively stable within the range of 18.2 and 18.7 cm.

For sugar beet the standard error remained almost the same (around 0.23) for all speeds. For wheat the standard error increases from 0.22 to 0.37 cm when speed increased from 4 to 8 km/h.

6.5. Coefficient of precision – CP3

The coefficient of precision (CP3) is the percentage of seed spacing that occurred within a 3 cm range centred on the mode spacing. According to Panning et al. (1997) this parameter was proposed by Smith et al. (1991) and adopted by researchers at L'Institut Technique Francais de la Betterave Industrielle (1994). Its popularity has been growing since because it is a very good way to represent the ability of a planter to space seeds near the true planter spacing setting. The mean CP3 values for both seeds for 4, 6 and 8 km/h are shown in Table 6.6 and Figure 6.5.

Table 6.6: CP3 means and standard errors

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (%)	SE (%)	Prediction (%)	SE (%)
4	56.9	4.96	56.0	4.96
6	41.9	4.96	38.3	4.96
8	60.8	4.96	26.2	4.96

LSD = 15.6

To investigate the influence of seed type and speed on CP3, a two-way ANOVA in randomised blocks was accomplished, using the GenStat software. This time it was used a balanced design because this index was calculated for all replications resulting in a constant number of values for seed and speed. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There was a significant difference in CP3 means for speed (P=0.019)
- There was a highly significant difference in CP3 means for seed (P=0.009)

- There was a significant difference in CP3 means for speed and seed (P=0.012)

The residual degrees of freedom was 10

6.5.1. Comparison of mean CP3 between speeds for sugar beet

The results show a significant difference (5% level) in the CP3 means between 6 and 8 km/h. However there was no significant difference (5% level) in the CP3 means between 4 and 6 km/h and between 4 and 8 km/h. This result is quite interesting because there is a strong evidence that the performance of the precision punch planter improved when the speed increased from 6 to 8 km/h. This improved performance was probably caused by better seed transfer from the seed metering unit into the delivery punches at higher speeds. During the experiments it was observed that incorrect deliveries were occurring. To produce an 18 cm seed spacing the machine was supposed to deliver a seed to an opened hole and then skip five holes before delivery of the next seed. But often a seed was found after four or six empty holes. Figure 6.4 shows this problem graphically as has been discussed before.

Looking through the metering window it was possible to see a seed being transferred from the metering disc into the wrong punch. Seeds should move only radially during seed transfer but sometimes the ejector moved them radially and laterally, which caused the errors. At this point the seeds were moved just a couple of millimetres away but once inside the wrong punch they were placed in the soil 3 cm away from the correct position.

This malfunction caused a big penalty for the performance of the punch planter. Every time a single wrong delivery happened two wrong seed spaces were produced reducing the CP3 value significantly. The CP3 value for 8 km/h was however impressive because it matches typical CP3 values achievable by commercial precision drills, and it can be significantly improved by solving the seed selection, ejection and transfer problems. An examination of the seed spacing histograms for 8 km/h shown in Figure 6.4 reveals that if the seed metering unit had successfully selected seeds most of them would be placed within a 3 cm range of variation, and in this case the CP3 value would be close to 100%.

6.5.2. Comparison of mean CP3 between speeds for wheat

The results show a significant difference (5% level) in the CP3 means between speeds 4 km/h and 6 km/h, and between speeds 4 and 8 km/h. There was no significant difference (5% level) in the CP3 means between speeds 6 and 8 km/h. These results shows that the performance of the precision punch planter was very much influenced by speed for wheat. The punch planter had a good performance only at 4 km/h. When the speed was increased to 6 km/h the CP3 reduced significantly. Between 6 and 8 km/h the difference was not significant and the CP3 value remained low. For wheat the low CP3 values were not only due to poor seed selection at 6 and 8 km/h but also poor seed transfer into the delivery punches at all speed.

6.5.3. Comparison of mean CP3 between seeds for speeds

The results show no significant difference (5% level) in the mean seed spacing for sugar beet and wheat when the planter was tested at 4 and 6 km/h. But for 8 km/h there was a significant difference (5% level) in the mean CP3 value between sugar beet and wheat. The results show that for sugar beet 60.8% of the seed spaces produced by the machine was inside the 3 cm range centred on the mode and for wheat only 26.2% , when the machine was working at 8 km/h.

6.6. Quality of feed index – A

The quality of feed index is the percentage of seed spacing that are between 0.5 and 1.5 times the theoretical seed spacing (9 > 27 cm). The mean quality of feed index values for both wheat and sugar beet seeds at 4, 6 and 8 km/h are shown in Table 6.7 and Figure 6.5.

Table 6.7: Quality of feed index (A) means and standard errors for seed and speed

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (%)	SE (%)	Prediction (%)	SE (%)
4	91.4	4.24	88.8	4.24
6	88.4	4.24	74.3	4.24
8	80.1	4.24	55.6	4.24

LSD = 13.4

To investigate the influence of seed type and speed on quality of feed index, a two-way ANOVA in randomised blocks was accomplished, using the GenStat software. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There was a very highly significant difference in quality of feed index – A means for speed (P=0.001)
- There was a highly significant difference in quality of feed index – A means for seed (P=0.003)
- There was no significant difference in quality of feed index – A means for speed and seed (P=0.077)

The residual degrees of freedom was 10

6.6.1. Comparison of mean quality of feed index (A) between seeds

The mean quality of feed index (A) values for seed type are shown in Table 6.8. The analysis of variance shows a significant difference between the quality of feed index (A) means for seeds. The results show that the punch planter prototype had a better performance for sugar beet with 86.6% of all seed spaces produced within the range of 0.5 to 1.5 times the theoretical seed spacing o f18 cm. For wheat the figure was reduced to 72.9%. This index was strongly influenced by poor seed selection mainly for wheat. If this problem is solved this index would be close to100% even if incorrect seed transfers into the delivery punches continues to happen.

Table 6.8: Quality of feed index (A) means and standard errors for seed type

Seed			
Sugar beet		**Wheat**	
Prediction (%)	SE (%)	Prediction (%)	SE (%)
86.6	2.45	72.9	2.45

LSD = 7.7

6.6.2. Comparison of mean quality of feed index (A) between speeds

The mean quality of feed index (A) values vs. speed are shown in Table 6.9. The analysis of variance shows no significant difference between the quality of feed index means at 4 and 6 km/h, however it was almost significant at 5 % level. The difference between this index's means are significant when comparing 6 with 8 km/h and 4 with 8 km/h. These results show a progressive reduction on the machine ability to place seeds within the range of 0.5 to 1.5 times the theoretical seed spacing when both seeds are considered all together. The previous comparison suggests that this reduction was caused by the poor performance for wheat.

Table 6.9: Quality of feed index (A) means and standard errors for speed

Speed	**Sugar beet and Wheat**	
(km/h)	Prediction (%)	SE (%)
4	90.1	3.0
6	81.3	3.0
8	67.9	3.0

LSD = 9.4

6.6.3. Comparison of mean quality of feed index (A) for seeds and speeds

Although the analysis of variance showed that the difference in the quality of feed index means were not significant for interactions between seed and speed, a comparison will be made as another reference because it was almost significant at 5 % level.

The analysis of variance shows that for sugar beet there was no significant difference (5% level) in the quality of feed index means for all speeds tested. The planter maintained its ability to place seeds within the range of 0.5 to 1.5 times the theoretical seed spacing (18 cm) for all speeds tested.

For wheat the analysis of variance shows that there was significant differences (5% level) in the quality of feed index means between all speeds tested. As the speed increased, the planter lost its ability to place seeds within the range of 0.5 to 1.5 times the theoretical seed spacing (18 cm). From 4 to 8 km/h this index reduced from 88.8% to only 55.6%.

When both seeds are compared for every speed the ANOVA shows that there was no significant difference at the 5% level in the quality of feed index means between seeds at 4 km/h. This similarity on the performance of the prototype for both seeds did not occur at higher speeds. The results show a significant difference in the quality of feed index means between seeds at 6 and 8 km/h.

6.7. Missing index - M

The missing index (M) is the percentage of seed spacing that are greater than 1.5 times the theoretical seed spacing (18 cm). The mean missing index (M) values for both seed and speed are shown in Table 6.10 and Figure 6.5.

Table 6.10: Missing index (M) means and standard errors for seed and speed

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (%)	SE (%)	Prediction (%)	SE (%)
4	8.6	3.83	11.2	3.83
6	11.6	3.83	23.4	3.83
8	18.8	3.83	42.8	3.83

LSD = 12.1

To investigate the influence of seed type and speed on the missing index, a two-way ANOVA in randomised blocks was accomplished, using the GenStat software. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There is a very highly significant difference in the missing index (M) means for speed ($P<0.001$)
- There is a highly significant difference in the missing index (M) means for seed ($P=0.002$)
- There is no significant difference in quality of feed index (M) means for speed and seed ($P=0.055$)

The residual degrees of freedom was 10

6.7.1. Comparison of mean missing index (M) between seeds

The mean missing index (M) values for seed type are shown in Table 6.11.

Table 6.11: Missing index (M) means and standard errors for seed type

Seed			
Sugar beet		**Wheat**	
Prediction (%)	SE (%)	Prediction (%)	SE (%)
13.0	2.22	25.8	2.22

LSD = 7.0

The analysis of variance shows a significant difference in the missing index (M) means between seeds. The results show that the seed metering unit of the punch planter had a better performance for sugar beet (M = 13%) than for wheat (M = 26%). However the missing index means were high for both seeds indicating that the seed metering unit needs further optimisation to improve seed selection for both seeds.

6.7.2. Comparison of mean missing index (M) between speeds

The mean missing index (M) values for speeds are shown in Table 6.12. The analysis of variance shows that the difference for the missing index's means between 4 and 6 km/h was not significant at the 5 % level. But the difference between this index means were significant (5% level) when comparing 6 with 8 km/h and 4 with 8 km/h.. The results show that the machine has its ability to select seeds significantly reduced when operated at 8 km/h. Again the previous comparison suggests that this reduction was caused by the poor performance for wheat.

Table 6.12: Missing index (M) means and standard errors for speed

Speed	**Sugar beet and Wheat**	
(km/h)	Prediction (%)	SE (%)
4	9.9	2.71
6	17.5	2.71
8	30.8	2.71

LSD = 8.5

6.7.3. Comparison of mean missing index (M) between seeds and speeds

This comparison was made despite the analysis of variance had shown no significant difference for interactions between seed and speed for the missing index means. This difference was almost significant at the 5 % level.

For sugar beet the analysis of variance shows that there was no significant difference (5% level) in the missing index means for all speeds tested. The results suggest that planter maintained its ability to select seeds for all speeds tested.

For wheat the analysis of variance shows that there was significant differences (5% level) in the missing index means between 6 and 8 km/h and between 4 and 8 km/h. As the speed increased to 8 km/h the planter had its ability to select seeds significantly reduced. From 4 to 8 km/h the missing index increased almost four times, from 11.2% to 42.8%.

When both seeds are compared for every speed the ANOVA shows that there was no significant difference (5% level) in the missing index means between seeds at 4 and 6 km/h. But there was a significant difference (5% level) in the missing index means between seeds at 8 km/h.

6.8. Multiple index – D

The multiple index (D) is the percentage of seed spacing that are less than or equal to 0.5 times the theoretical seed spacing of 18 cm. Therefore it shows the percentage of seed spaces created by multiple seed selection. The mean multiple index (D) values for both seed and speed are shown in Table 6.13 and Figure 6.5.

Table 6.13: Multiple index (D) means and standard errors for seed and speed

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (%)	SE (%)	Prediction (%)	SE (%)
4	0	1.22	0	1.22
6	0	1.22	2.3	1.22
8	1.0	1.22	1.6	1.22

LSD = 3.8

To investigate the influence of seed type and speed on the multiple index, a two-way ANOVA in randomised blocks was accomplished, using the GenStat software. The complete results of the ANOVA are shown in the Appendix C, it showed that:

- There was no significant difference in the multiple index (D) means for speed (P=0.530)
- There was no significant difference in the multiple index (D) means for seed (P=0.359)
- There was no significant difference in the multiple index (D) means for speed and seed (P=0.633)

The residual degrees of freedom was 10

The multiple index (D) was very low for sugar beet and wheat for all speeds tested. The results show that the metering unit worked properly in relation to the number of seed selections per punch. Double selections were very rare. The grand mean for the multiple index (D) was 0.82%

6.9. Precision – C

Precision (C) is a measure of variability in spacing between seeds around the target spacing. It is the sample standard deviation (of the seed spacing within the range of 0.5 to 1.5 times the theoretical spacing - 9 to 27 cm) divided by the theoretical seed spacing (18 cm). Precision (C) is similar to the coefficient of variation of the seed spacing that are classified as singles. It differs from the usual coefficient of variation in that it uses the theoretical seed spacing as the denominator in place of the sample mean.

The precision (C) is not affected by the outliers because its calculation does not take into account any seed spacing outside the target range. Multiples and skips are removed. It will only measure the degradation of performance within the target range. The maximum theoretical value for precision is 50%. It happens when half of the seed spaces are at the lower limit and half are at the upper limit of the target range. This would indicate that the theoretical spacing was incorrectly specified. A precision of 29% would indicate that all seed spaces are uniformly spread within this range.

The mean precision (C) values for both seed and speed are shown in Table 6.14 and Figure 6.5.

Table 6.14: Precision (C) means and standard errors for seed and speed

	Seed			
Speed	**Sugar beet**		**Wheat**	
(km/h)	Prediction (%)	SE (%)	Prediction (%)	SE (%)
4	10.7	1.58	12.4	1.58
6	13.3	1.58	12.3	1.58
8	10.2	1.58	14.1	1.58

LSD = 5.0

The grand mean for the precision (C) was 12.2%. This shows that the standard deviation of the seed spacing within the target range is 12.2% of the theoretical seed spacing of 18 cm. This grand mean was much lower than the practical upper limit of 29% demonstrating concentration of seed placement around the target seed spacing.

To investigate the influence of seed type and speed on precision, a two-way ANOVA in randomised blocks was accomplished, using the GenStat software. The complete results of the ANOVA are shown in the Appendix C, it showed that:

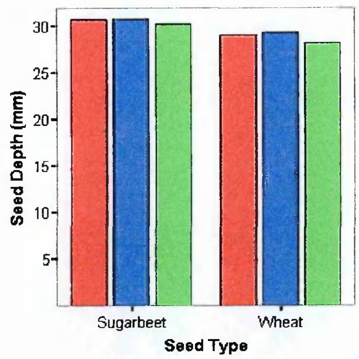
- There was no significant difference in precision (C) means for speed (P=0.728)
- There was no significant difference in precision (C) means for seed (P=0.256)
- There was no significant difference in precision (C) means for speed and seed (P=0.321)

The residual degrees of freedom was 10

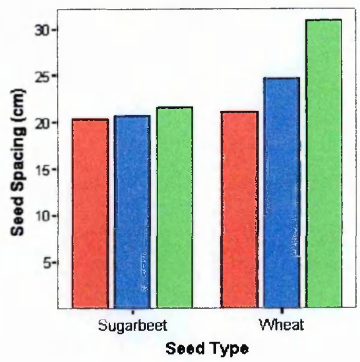
The values for precision (C) are almost the same for both seeds and for all speeds tested. This stability is a very good result showing that once a seed had been selected, the punch planter precisely delivered and placed them very close to the target spacing for both seeds sugar beet and wheat and for all speeds tested. An examination of the histograms helps to visualise the figures above. Seed distribution was never spread out within the target range but it was always concentrated in the middle of it.

1.10. Overview of measures of accuracy

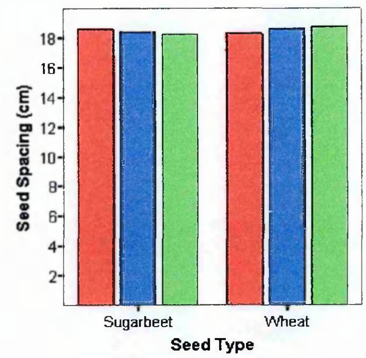
An overview of the eight measures of accuracy used is shown in figure 6.5. The LSD values for the first three graphs are not shown because it was used an unbalanced design due to different number of measurements for seed type and speed. The LSD values for the mean seed spacing are shown in Table 6.4. For the mean seed depth and mean seed spacing within the target range these values can be found in Appendix C.



Mean seed depth

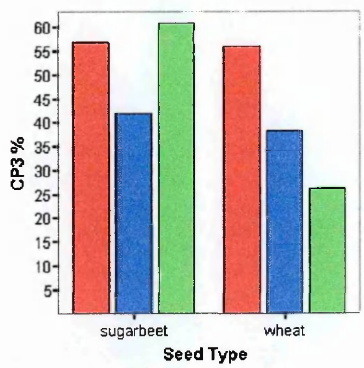


Mean seed spacing



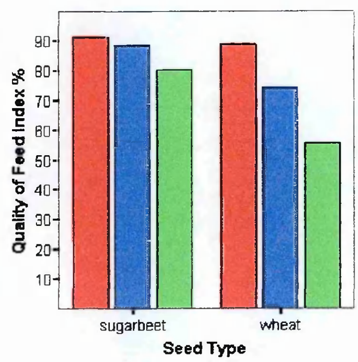
Mean seed spacing

Within the target region



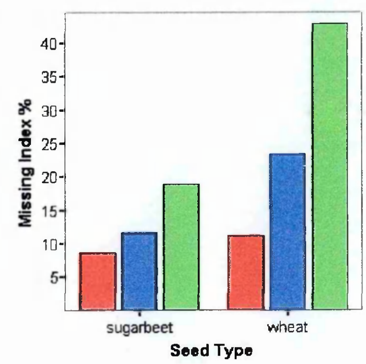
Mean CP3

(LSD = 15.6)



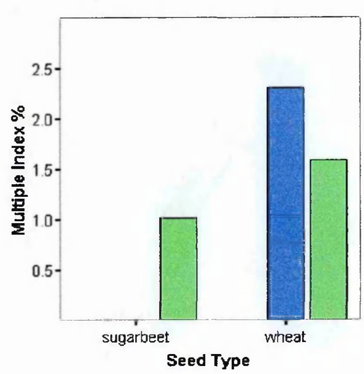
Mean quality of feed index

(LSD = 13.4)



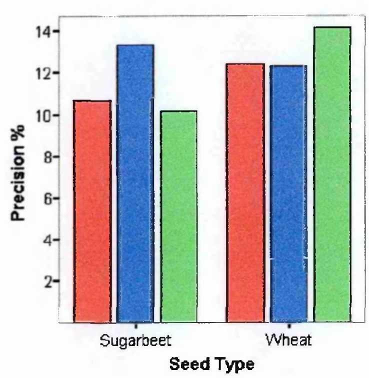
Mean missing Index

(LSD = 12.1)



Mean multiple index

(LSD = 3.8)



Mean precision

(LSD = 5.0)

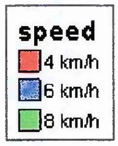


Figure 6.5: Measures of accuracy

7. Discussion

The soil bin evaluation of the precision punch planter prototype revealed strong aspects and weak points of the solution developed. The results show that the prototype had precise control of seed delivery and placement for both seeds, wheat and sugar beet, at all speeds - 4, 6 and 8 km/h, when a seed had been selected and transferred properly. However, problems with seed selection, reduced the precision and reliability of the prototype, producing seed spaces twice, three times, and even four times the target spacing of 18 cm. Problems with seed transfer into the delivery punches were also revealed, creating undesirable dispersion around the target spacing.

The planter developed has shown potential to produce equidistant seed spacing distribution in all directions, and also measure seed locations in the field. In order to fully explore the potential of the solution developed, the seed metering unit needs to be modified to improve seed selection and transfer. Following, the results are discussed in detail and the performance of the prototype is compared with the performance of commercial drills and also previous developments of punch planters.

7.1. Measures of accuracy

Before discussing about the measures of accuracy obtained, some results from previous research about punch planter and from performance evaluation for commercial sugar beet drills will be presented. This information will be used as reference to determine the strength of the solution developed, and also to establish how much development is needed to improve precision and accuracy on seed placement to achieve higher levels of precision than the ones obtained by successful precision drills available on the market.

The most successful punch planter found during the literature review was developed by Molin et. al. (1997) and was reviewed in Chapter 3. The results of their field evaluation of the prototype is shown in Table 7.1 for comparison. The prototype was evaluated in a silt loam soil, direct drilling over three types of residue cover, at three speeds, and using three punch wheel sizes. A commercial seed metering unit operated by vacuum

Table 7.1: Measures of accuracy for field evaluation of the punch planter prototype developed and evaluated by Molin et. al. (1997)

Punch wheel Diameter (mm)	Speed (km/h)	Multiples Index (%)	Quality of feed index (%)	Miss index (%)	Precision (%)
Maize residue					
650	5.4	3.6	64.3	32.1	14.42
	7.2	2.0	76.7	21.3	12.70
	9.0	0.4	78.3	21.3	12.88
825	5.4	7.6	52.6	39.8	12.06
	7.2	3.2	65.1	31.7	9.33
	9.0	1.6	72.3	26.1	11.07
1000	5.4	3.6	57.4	39.0	10.25
	7.2	11.2	38.6	50.2	9.15
	9.0	0.8	63.1	36.1	11.12
LSD (0.05)		4.38	14.46	11.80	3.231
Pr > F (%)		0.0011	0.0004	0.0011	0.0458
Grain sorghum residue					
650	5.4	0.8	81.5	17.7	11.45
	7.2	2.8	67.9	29.3	10.51
	9.0	1.2	80.3	18.5	11.17
825	5.4	2.8	63.9	33.3	8.05
	7.2	0.8	68.7	30.5	8.62
	9.0	1.2	81.1	17.7	9.27
1000	5.4	5.2	53.0	41.8	7.64
	7.2	8.8	49.8	41.4	6.66
	9.0	0.8	75.5	23.7	7.93
LSD (0.05)		3.92	15.41	12.55	2.392
Pr > F (%)		0.0051	0.0017	0.0020	0.0046
Soybean residue					
650	5.4	2.0	82.3	15.7	12.51
	7.2	1.2	78.7	20.1	11.81
	9.0	0.4	81.9	17.7	10.58
825	5.4	4.4	75.1	20.5	11.40
	7.2	0.4	82.7	16.9	11.29
	9.0	2.4	75.5	22.1	11.28
1000	5.4	3.6	72.7	23.7	9.14
	7.2	7.6	60.6	31.7	8.13
	9.0	0.8	82.3	16.0	7.67
LSD (0.05)		5.38	21.92	18.12	3.393
Pr > F (%)		0.1642	0.5110	0.7182	0.0749

was used. Plant spacing was measured and not seed spacing. As a result, the effects of emergence could have affected their results.

Smith et. al. (1991) compared the seed spacing uniformity of two general-purpose U.S. drills and an European precision drill for pelleted sugar beet seeds. The experiments were done in the field but soil type and conditions were not reported. Seed spacing was measured by excavating the seeds after drilling. The measure of accuracy used to compare the performance of the drills in relation to seed placement was the CP3. Their results are shown in Table 7.2 for reference. Note how CP3 values decreased as speed increased for all five drills. However the precision drill Unicorn – 3, manufactured by Kleine, had a much better performance for all speeds tested.

Table 7.2: Mean CP3 for drill type at 3.2, 5.6 and 8 km/h, obtained by Smith et. al. (1991) in a field evaluation.

Planter Type	3.2 km/h	5.6 km/h	8 km/h
Kleine Unicorn-3	74.7	68.4	60.4
Max Emerge - Metal Tube	54.9	40.8	36.7
Max Emerge - Sugar beet tube	56.4	43.6	22.7
Max Emerge - Insert Tube	35.4	27.2	18.7
John Deere 71	40.4	21.7	17.1

A field evaluation of five precision drills for sugar beet was accomplished by Profi International (1999). The evaluation was done in a medium clay silt soil. The models and manufacturers of the precision drills tested were respectively: Centra 2000 from Becker, Unicorn synchro-drive from Kleine, Monopill from Kverneland Accord, Meca 2000 from Monosem and UD 3000 from Schmotzer. The best values of several measures of accuracy for 6.5, 7.2 and 8.0 km/h are shown in Table7.3. Plant spacing was measured and not seed spacing, therefore the effect of emergence could have influenced their results. Instead of using CP3, a similar measure of accuracy was used, which was called CP5 (Table 7.3), because it is the percentage of seed spaces produced that are within plus or minus 2.5 cm of the mode spacing. All five precision drills produced very high precision and reliability on seed placement in the field, revealing a strong competition among them and a high standard of performance to be overcome.

Table 7.3: Mean actual spacing, mean seed depth, and best values for the others measures of accuracy obtained by Profi International (1999).

Travel speed	6.5 km/h	7.2 km/h	8.0 km/h
Mean actual spacing (cm)	19.7	20.0	19.9
Minimum multiple index – D (%)	1.4	1.4	1.1
Maximum quality of feed index – A (%)	87.3	86.9	87.5
Minimum missing index – M (%)	11.3	11.6	11.1
Maximum CP5 (%)	85.7	83.0	82.2
Mean seed depth (cm)		3.1	
Minimum coeff. of variation for seed depth (%)		22	

7.1.1. Coefficient of precision - CP3

The CP3 achieved by the punch planter for wheat decreased from 56.0 % at 4 km/h to 38.3 % at 6 km/h and then to 26.2% at 8 km/h. For sugar beet these figures were 56.9, 41.9 and 60.8 % respectively. This difference in behaviour was unexpected because the seed metering unit generally became less reliable as speed increased. Therefore it was expected a reduction of CP3 values as speed increased for both seeds. To investigate this problem, the CP3 values were subtracted from the quality of feed index values obtaining the percentage of seed spacing created due to incorrect seed transfers into neighbouring holes. These incorrect seed transfers varied from 32.8 % at 4 km/h to 36.0 % at 6 km/h and to 29.4 % at 8 km/h for wheat, remaining relatively stable. For sugar beet these figures were 34.5 %, 46.5 % and 19.3 % respectively, revealing strong influence of the travel speed. It seems that the ball shape of pelleted sugar beet seeds had a strong influence on the trajectory of seeds during ejection and transfer. The improvement on seed transfer for sugar beet seeds at 8 km/h, is therefore counterbalanced by the loss of performance due to missing seeds.

Eliminating the problem with seed transfer would significantly increase CP3 values. For wheat the CP3 values would have been: 88.8 % (56.0 % + 32.8) at 4 km/h, 74.3 % (38.3 % + 36.0 %) at 6 km/h, and 55.6 % (26.2% + 29.4 %) at 8 km/h, if all seeds had been correctly transferred into the respective delivery punch. For sugar beet these figures would have been: 91.4 % (56.9 % + 34.5%), 88.4 % (41.9 % + 46.5 %) and

80.1 % (60.8 % + 19.3%) respectively. Solving the problem with seed transfer, would make the ability of the punch planter prototype to place seeds in the soil within a 3 cm range only dependent of seed selection due to the high performance of the seed delivery.

The CP3 values obtained in the soil bin were lower than the ones obtained by Smith et. al. (1991) in the field (Table 7.2) using the Kleine Unicorn-3 sugar beet precision drill, except for sugar beet at 8 km/h, where CP3 values were similar. The CP3 values that would have been obtained for sugar beet, if seeds had been correctly transferred, would have matched typical CP3 values for sugar beet precision drills commercially available. For 8 km/h, for example, the CP3 value that would have been obtained is 80.1 % and the best result obtained by Profi International (1999), during their field evaluation of five precision drills for sugar beet (Table 7.3) was a CP5 of 82.2 %. Note that CP5 (range of 5 cm) was used instead of CP3 (range of 3 cm). However, plant spacing was measured and not seed spacing.

The benchmark established by current precision drills for sugar beet could be overcome by the punch planter developed if the seed transfer problems are solved and seed selection is improved. The seed metering unit of current drills for pelleted sugar beet seeds achieve 99 % of seed selection at 8 km/h and the tangential velocity of seed cells match ground velocity. Therefore, if a seed metering unit of this type were used (diameter of 250 mm), the prototype would be running at 18.4 km/h while keeping the tangential speed of the seed cells at 8 km/h. In this case seed selection would not be a problem up to 18 km/h, which is an impressive speed for precision drilling. These results show that, the solution developed had an exceptional performance to precisely deliver and place seeds in the soil. For wheat, the results also encourage further developments of the seed metering unit to make it operate at higher speeds.

7.1.2. Precision

Precision (P) did not change significantly either for speed or seed. For wheat, precision was 12.4 % at 4 km/h, 12.3 % at 6 km/h and 14.1 % at 8 km/h. For sugar beet this measure was 10.7 %, 13.3 % and 10.2 % respectively. These results indicate that the prototype's performance in relation to seed placement was even, for both seeds and all three speeds tested, when the seed metering unit had selected seeds properly. However, the incorrect seed transfers that had reduced the CP3 values have also reduced the values of precision.

These results for precision (P) is inside the range of precision values obtained by Molin et. al. (1997) that are shown in Table 7.1. But Molin et. al. (1997) obtained lower values for precision for the two larger punch wheels than the ones obtained by the prototype developed here. These results indicate that, when the larger punch wheels were used, Molin et. al. (1997) obtained a better precision on seed placement, in the field. However, the punch planter developed by Molin et. al. (1997) does not vary seed spacing changing the number of active punches, therefore seeds are delivered to every punch. When seeds are incorrectly transferred into the wrong punch, it does not affect precision (P) because it creates seed spaces caused by double seed delivery and a missing seed. Consequently, only the multiple and missing indexes would be affected. For the prototype developed here, the incorrect seed transfers reduced the value of precision because incorrect seed spaces were created around the target spacing and inside the quality of feed index region, where the seed spaces used to calculate precision are.

The level of precision may be improved further once the problem with incorrect deliveries is solved. These indexes can be clearly visualised using the seed spacing histogram shown in Figure 6.2 and 6.4. For sugar beet at 6 km/h the value for precision was slightly higher due to an increase in incorrect seed transfers into the neighbouring punches.

7.1.3. Quality of feed index - A

For wheat seeds, the performance of the punch planter prototype in relation to seed selection significantly deteriorated as speed increased. The percentage of seeds within

0.5 and 1.5 times the target spacing (quality of feed index) decreased from 88.8 % at 4 km/h to 74.3 % at 6 km/h to 55.6 % at 8 km/h. This reduction was mainly caused by failure while selecting seeds and not by double seed selections. For pelleted sugar beet seeds, the quality of feed index decreased from 91.4 % at 4 km/h to 88.4 % at 6 km/h and to 80.1 % at 8 km/h. Seed selection had also deteriorated as speed increased, but in a moderate way.

The results obtained during this research for the quality of feed index for sugar beet were higher than the ones obtained by Molin et. al. (1997) (see Table 7.1) and similar to the ones obtained for wheat (excluding 8 km/h). These comparisons must be analysed with care because the effect of emergence could have affected their results reducing the quality of feed index value. However, it suggests that a relatively good performance was achieved by the punch planter. It is important to consider that the seed metering unit used for this research was completely designed and built for the prototype, because it had to be fitted inside the double punch wheel mechanism and rotates with it. Molin et. al. (1997) had used a commercial seed metering unit operated by vacuum that had its orientation altered to be installed inside the punch wheel.

The best Quality of feed index obtained by Profi International (1999) in a field evaluation of five precision drills for sugar beet (Table 7.3) for 8 km/h was 87.5 %. Plant spacing was measured and not seed spacing, therefore emergence might have reduced this index, but the values obtained for quality of feed index for sugar beet for this research were similar to the ones shown in Table 7.3. For wheat they were similar at 4 km/h and much lower at 6 and 8 km/h. This comparison indicates that the benchmark for the redesign of the seed metering unit to improve seed selection is relatively close to be achieved.

7.1.4. Missing index - M

The missing index for wheat increased almost at the same proportion that the quality of feed index had decreased. It increased from 11.2 % at 4 km/h to 23.4 at 6 km/h to 42.8

at 8 km/h. For sugar beet it was 8.6, 11.6 and 18.8 respectively. This result shows how much improvement is needed for seed selection. Reliable wheat seed selection at high speeds (8 km/h) is a difficult task to be accomplished due to the irregular shape of the seeds. However, seed selection by vacuum is a proven solution commercially for a wide range of seeds. The seed metering unit has not been fully optimised during this work, because design effort was concentrated in the development of a concept that has an efficient combination of working principles. The relationship between the working principles proved to be efficient, but there is a lot of opportunities to improve the performance of the prototype, mainly in relation to seed selection.

The results for the missing index obtained during this research for sugar beet were lower than the ones obtained by Molin et. al. (1997) (see Table 7.1) . For wheat it was similar for 4 and 6 km/h and slightly higher for 8 km/h.

The lowest missing index obtained by Profi International (1999) in a field evaluation of five precision drills for sugar beet (Table 7.3) for 8 km/h was 11.1 %, which could have been affected by emergence. This index is a complement of the previous, therefore the same level of improvement is required for this index and the quality of feed index.

7.1.5. Multiple index - D

The multiple index values complement the entire seed spacing spectrum with the few remaining percentages. For wheat, it varied from 0 % at 4 km/h to 2.3 % at 6 km/h and finally to 1.6% at 8 km/h. For sugar beet these figures were 0 , 0 and 1.0 % respectively. The results show that seed singulation was efficiently accomplished by the prototype, which reached the same levels achieved by Molin et. al. (1997) and by Profi International (1999).

7.1.6. Mean seed spacing

The mean seed spacing increased significantly with speed for both seeds. It increased from 21.1 % at 4 km/h to 24.7 % at 6 km/h and to 30.9 % at 8 km/h. The mean seed spacing was affected mostly by the missing seeds. Double seed selection can also affect the mean seed spacing but this type of error was rare. Errors due to incorrect seed transfer does not affect the mean seed spacing because this type of error is symmetrically distributed around the target. The mean seed spacing was affected mostly by the missing seeds. Errors due to incorrect seed transfer does not affect the mean seed spacing because this type of error are symmetrically distributed around the target. The mean seed spacing for sugar beet seeds also increased significantly with speed. It increased from 20.3 cm at 4 km/h to 20.5 cm at 6 km/h to 21.6 cm at 8 km/h.

7.1.7. Mean seed spacing within the target range

The mean seed spacing within the target range, when doubles and missing seeds are not considered, remained stable for both seeds all speeds. For wheat it was 18.3 % at 4 km/h, 18.6 % at 6 km/h and 18.7 % at 8 km/h. For sugar beet it was 18.6 cm at 4 km/h, 18.4 cm at 6 km/h and 18.2 cm at 8 km/h. This measure shows the actual seed spacing produced, which was close to the target spacing of 18 cm.

7.1.8. Mean seed depth

The punch planter prototype produced uniform seed depth for both seeds at all speeds tested. For wheat the mean seed depth was 29.1 % at 4 km/h, 29.4 % at 6 km/h and 28.2 % at 8 km/h. For sugar beet the mean seed depth was 30.7 mm at 4 km/h, 30.7 mm at 6 km/h and 30.2 mm at 8 km/h.

The coefficient of variation for seed depth was 13.7 %. The lowest coefficient of variation for seed depth obtained by Profi International (1999) (Table 7.3.) in the field was 22 %.

7.2. Machine Performance

The seed spacing histograms for 4, 6 and 8 km/h were categorized by error source on seed placement, and are shown in Figures 7.1 for wheat and Figure 7.2 for sugar beet. A seed spacing interval of 5 mm was used to show the seed spacing spectrum with intermediate focus between the two previous intervals used (10 and 2 mm). The last bar in all histograms shows seed spaces that are greater than 44 cm. These histograms show that most seeds were placed within ± 1.5 cm around the mode spacing, which was close to the target spacing of 18 cm, for both seeds and for all speeds. However, the effect of seed selection and seed transfer problems can be clearly identified in all histograms.

Incorrect seed transfers between the seed metering unit into the delivery punches produced seed spaces around the mode spacing (± 3 cm) the seed spacing increment. These incorrect seed transfers occurred for both seeds at all speeds and were observed during the tests through the seed metering, but could not be solved. For sugar beet, incorrect seed transfer was the main predominant factor limiting the performance of the machine.

When the seed metering unit failed to select seeds, seed spaces equal to twice the mode spacing (± 1.5) cm were created. Seed selection failures occurred for both seeds and increased with speed, but for wheat it was the predominant problem. Seed selection failures sometimes were combined with incorrect seed transfers creating seed spaces around two times the mode spacing (± 3 cm).

Double seed selections were rare for both seeds at all speeds, therefore the seed metering unit could select single seeds efficiently.

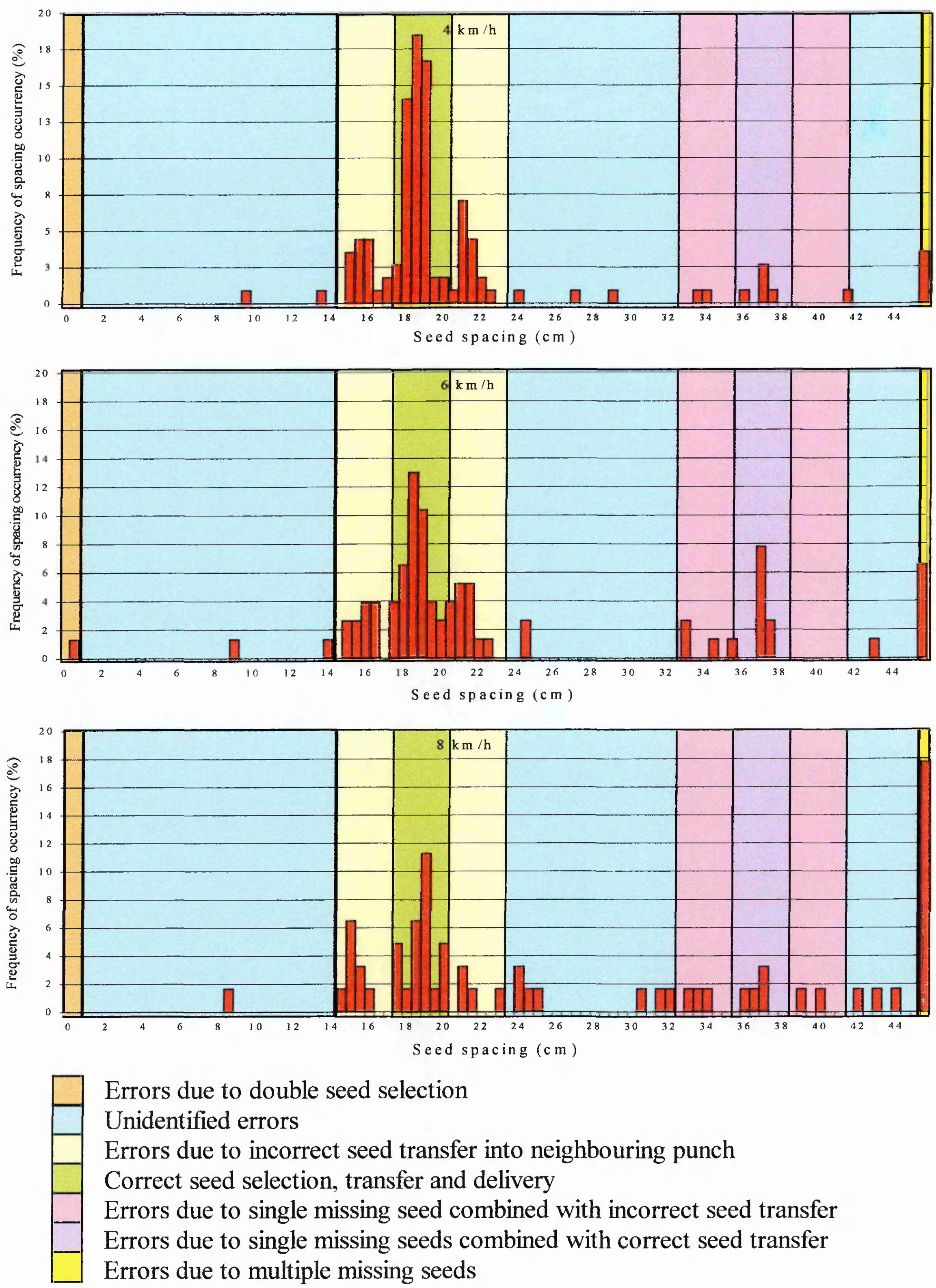


Figure 7.1: Seed spacing histograms (4, 6 and 8 km/h) for wheat seeds categorized by source of error on seed placement. Seed spacing intervals: 5 mm

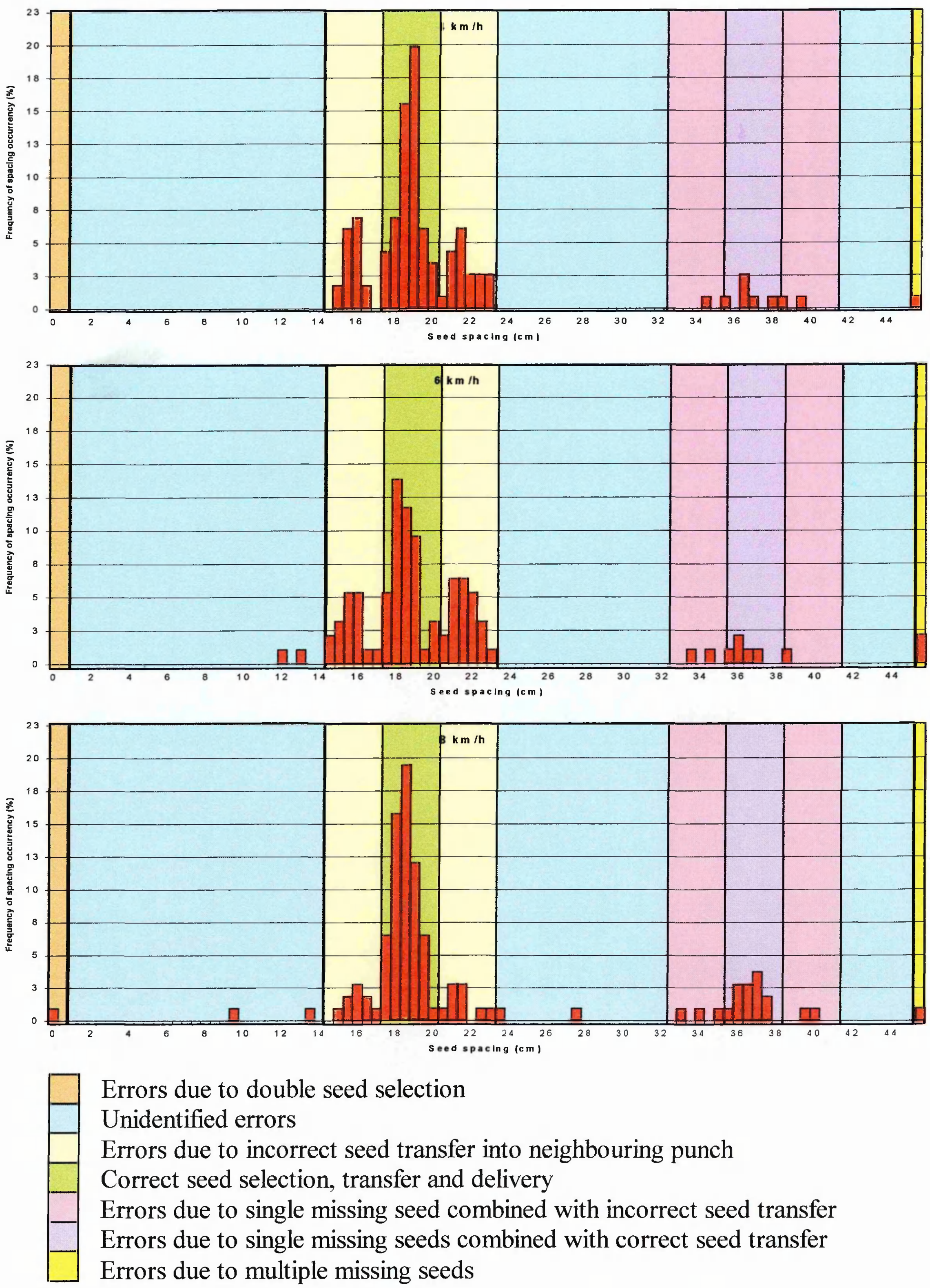


Figure 7.2: Seed spacing histograms (4, 6 and 8 km/h) for pelleted sugar beet seeds categorised by source of error on seed placement. Seed spacing intervals: 5 mm

Few seeds were found inside the remaining regions of the seed spacing spectrum, which was categorised as unidentified error source. This category represents a significant portion of the seed spacing spectrum. The seed spaces produced within this region were caused by loss of control on seed placement.

These histograms shows that, apart from seed selection and transfer problems, the punch planter prototype had precise control of seed placement.

7.2.1. Errors due to double seed selection

Errors due to double seed selections produce seed spacing around zero centimetres. This type of error were very rare and must be avoided in any circunstance because both seeds are delivered into the same hole in the soil promoting strong competition within the crop. This is divergent from the research objectives. Seed singulation is a relatively easy task to be executed in a vacuum operated seed metering unit. Usually a brush or a serrated singulator is used. The prototype had a brush type seed singulator which slightly touched seeds being selected to remove multiple selections. This seed singulator was kept fixed in position during all tests. The multiple index (D) indicates the percentage of seed spacing within 0 and 9 cm therefore it is the best measure of accuracy to evaluate the performance of the prototype in relation to double seed selection. Note that the multiple index may also have included some seed spaces that were classified as unidentified error in Figures 7.1 and 7.2.

7.2.2. Unidentified errors

Unidentified errors were created when the prototype completely lost control of seed placement. The unidentified errors might have been created due to various causes. A single or double seed selection followed by a premature release of one seed might produce this type of seed spacing. Seeds might have been removed from the holes by the punch as it leaves the soil and instead placed a seed inside an incorrect hole. Delays on seed delivery might have caused seeds to leave the tip of the punches after the punch had left the soil causing incorrect delivery. This type of error affects all measures of accuracy but they were rare, showing that the prototype, in general, did not loose control of seed placement.

7.2.3. Errors due to incorrect seed transfer into neighbouring punch

Some errors were created when seeds were incorrectly transferred into a neighbouring punch. These incorrect seed transfers had been observed from the seed metering windows during calibration of the seed releasing point but could not be resolved. This type of error was frequent during the experiments, deteriorating the prototype's ability to precisely place seeds in the soil. Each time one fault of this type had occurred, two incorrect seed spacing were created introducing a ±3 cm error on seed placement. As a consequence, the coefficient of precision (CP3), which indicates the percentage of seed spacing within 3 cm range centred on the mode, were significantly reduced. Precision (C), which indicates the variability in spacing between seeds around the target spacing, was also affected by this problem. Therefore this problem was reflected on these two measures of accuracy.

Seed ejection and transfer must be executed efficiently not only to produce a uniform seed spacing but also to allow seed spacing measurements using simple and cheap instrumentation. To improve seed ejection and transfer it is recommended to reduce the seed path during transfer, to optimise the shape of the punch opening which receive seeds and to provide adjustment for the seed disc.

The distance between the seed disc holes and the delivery punches can be reduced to place seeds closer to the punch openings at the moment of seed ejection and transfer. This change may be very effective to avoid seeds being delivered into wrong punches. The external wall of the metering cover must have its thickness reduced from 1.5 mm to around 0.5 mm. The seed singulator would need to be modified because of the lack of space available.

The delivery punch openings which receive seeds were manually manufactured using a file therefore its shape and dimensions are not precise. These openings must be made precisely to facilitate seed capture.

The seed disc was designed to rotate freely inside the metering vacuum chamber but the tolerances created an interference fit after pressing the punch to the wheel external disc. During the assembly the holes in the seed disc had been aligned with the middle of the delivery punches and could not be removed or rotated without damage. As a result seed position in relation to the delivery punches could not be varied. The seed disc orientation must be easily adjusted to place the seed disc holes at the proper position for seed ejection and therefore the manufacturing tolerances of these compontents must be improved to ensure a clearance fit.

7.2.4. Correct seed selection, transfer and delivery

Seeds that had been successfully selected, transferred and delivered were placed in the soil very precisely. Most seeds classified in this category were placed within a 2 cm range around the target. These are good results but this dispersion around the target might be reduced. The best measure of accuracy to evaluate this case is CP3 that shows the percentage of seed spaces within this category. Precision (P) also measures variability around the target spacing but it includes a larger portion of the seed spacing spectrum.

To improve seed placement around the target it is recommended to reduce the size and change the shape of the holes opened in the soil. Seeds can also be vertically orientated before seed placement in order to be fitted inside a smaller hole.

During this research a conservative approach was adopted while selecting the size of the holes to be opened in the soil and a 1 cm^2 base hole was used. Using this design, a wheat seed could be placed in any orientation with some extra space. This approach was taken because seeds could have been dragged out of the holes by the leaving punches if a smaller hole had been used. As this concern did not happened, it is recommended to reduce the size of the holes opened in the soil to increase precision around the target spacing. A reduction of 25 % is recommended.

Probably the best opportunity to improve precision around the target is optimising the shape of the punches which defines the hole shape. The punches were designed using a 10 x 20 x 1 mm box section made with low carbon steel. Therefore the punch tip needed to be designed with a 10 mm edge distributing the loads across a line to avoid material failure. It is recommended to optimise punch shape selecting a more robust material and trying to concentrate punch pressure on a point instead of a line. In this manner, when opposite punches get away from each other they create a hole shaped like an inverted wedge. Consequently seeds would be more precisely located at the target spacing guided by the inclined hole walls.

Wheat seeds have an elongated shape. Therefore, if they were vertically orientated prior to seed placement they could be fitted into smaller holes in the soil, increasing precision. It is recommended to investigate the possibility of implementing seed orientation, which may be executed simply through optimisation of the internal shape of the delivery tubes.

7.2.5. Errors due to single missing seed combined with incorrect seed transfer

The same type of error created around the target spacing also appeared around two times the target spacing (36 cm). Incorrect seed transfer was combined with a single missing seed introducing a ±3 cm error on seed placement around 36 cm. This type of error was less frequent than the one around the target spacing of 18 cm because two error causes should have happened simultaneously (no seed selection followed by an incorrect seed transfer) to create this type of error. These problems were reflected in the following measures of accuracy obtained: the coefficient of precision (CP3), the mean seed spacing, the quality of feed index (A) and the missing index (M).

To improve seed selection it is recommended to increase the vacuum level, optimise the seed discs, enlarge the vacuum ducts and increase the punch wheel diameter. It might not be necessary to make all these modifications and the first two recommendations should be the first improvements to be made. Enlarging the vacuum ducts and increasing the punch wheel diameter are relatively difficult to be made, therefore they should only be tried in case the seed selection could not be improved increasing vacuum and optimising the seed disc.

During the experiments a vacuum cleaner was used as a vacuum source which produced a vacuum of 26 mbar. This unit was operated at maximum capacity during all experiments therefore higher levels of vacuum could not be tested. The seed discs used during the experiments only had 10 holes to produce 18 cm of seed spacing. For the smallest seed spacing (3 cm) the seed disc must have 60 holes requiring a more powerful vacuum source to supply six times more holes with vacuum. For future research, it is recommended to use a more powerful vacuum source capable of producing up to 100 mbar.

During the experiments a plastic seed disc with 10 holes was used as a mask placed over a metal seed disc with 60 holes. This solution proved to be practical because several low cost discs could be constructed. On the other side, it was difficult to manufacture these discs with precise hole diameter. These plastic seed discs were also fragile, getting torn several times during the experiments. For future research it is recommended to use metal seed discs. Seed disc hole size must be optimised according to seed type, seed size and vacuum level.

The vacuum ducts which transfer vacuum from the shaft centre into the vacuum chamber behind the seed disc might be enlarged to improve the flow of air. The seal housing, which is also used to change the air flow direction through radial and axial holes might also be redesigned enlarging the vacuum ducts. These measures would need have a more beneficial effect when using seed discs with a high number of holes because they require an increased flow of air within the vacuum channels.

The punch wheel diameter can be increased to reduce the rotational speed of the punch wheels. This measure facilitates seed selection because the seed disc rotates slower with the punch wheel making seed pick up easier. It is important to keep the double punch wheel unit compact while increasing punch wheel diameter. Therefore, the angle between the punch wheels must be reduced in order to keep the unit width below 120 mm. The use of bigger punch wheels and smaller angle between them reduce the size of the holes opened in the soil. The results show that the hole size opened in the soil could be reduced, therefore it is recommended to increase the punch wheel diameter from 574 mm to 650 mm.

The number of punches must be kept at 60 to continue to obtain 6 distinct uniform seed spaces within the row. In this manner a wide range of seed density can be covered varying seed spacing in 6 steps using hole spacing as the seed spacing increment. While increasing the punch wheel diameter (keeping the number of punches fixed at 60) hole spacing will be increased, therefore, the seed spacing increment becomes bigger. As a result seed spacing is varied in bigger steps loosing flexibility but a wider range of seed spacing can be covered.

7.2.6. Errors due to single missing seeds combined with correct seed transfer

Errors due to faulty seed selection were considerable for pelleted sugar beet seeds and significant for wheat seeds mainly to higher speeds. Seed selection was poor in general and therefore must be improved. The coefficient of precision (CP3), the mean seed spacing, the quality of feed index (A) and the missing index (M) were all influenced by these problems as well. The same recommendations given in the previous section are also valid here to improve seed selection.

7.2.7. Errors due to multiple missing seeds

When the seed metering unit failed to select consecutive seeds a multiple missing error was created. The missing index (M) includes single and multiple missing seeds therefore the histograms shown in figures 6.1 and 6.3 should be used as reference for multiple missing seeds. This error is a really bad result for a precision drill, therefore it must be eliminated. It happened very rarely for pelleted sugar beet seeds but for wheat seeds this was a frequent problem, which increased significantly with speed. The seed metering unit must have its performance in relation to seed selection significantly improved mainly for wheat. The working principle of the seed metering unit used is very efficient while selecting seeds but the design was not optimised enough to produce reliable results.

The same recommendations given in the 7.2.5. section are also valid here to improve seed selection.

8. Conclusions

The following conclusions can be drawn from the study.

1. Precise seed placement in the soil controlling the pattern of plant distribution, and seed location in the field, to create seed maps, are fundamental to manage the crop at a plant-scale level.

2. Precision drilling is becoming attractive for wheat as seed rates have been reduced. Plant populations ranging from 50 to 140 plants/m^2 has been used in the UK, while early drilling wheat.

3. Rotary punch planters have an inherent potential produce equidistant seed spacing distribution in the field, controlling the seed paths from the seed metering unit to specific points in the soil. However, it has not been largely adopted due to reliability problems caused by punch clogging, difficulties to delivery seeds into the opened holes and difficulties to vary seed spacing.

4. A novel concept of punch planter was developed using three moving parts to place seeds in the soil, a fan and two inclined punch wheels. A precision punch planter prototype was designed and built using this concept. A vacuum operated seed metering unit and an air seed delivery system were used. Solutions were provided to avoid punch clogging, facilitate punch cleaning, vary seed spacing and delivery seeds into the opened holes.

5. The prototype exhibited CP3 values of 56.0 %, 38.3 % and 26.2 % for wheat seeds at 4, 6 and 8 km/h, respectively, in a soil bin evaluation of seed placement. For pelleted sugar beet seeds it exhibited CP3 values of 56.9 %, 41.9 % and 60.8 %, respectively.

6. The prototype exhibited Quality of Feed indexes of 88.8 %, 74.3 % and 55.6 % for wheat seeds at 4, 6 and 8 km/h, respectively. For sugar beet it exhibited Quality of Feed values of 91.4 %, 88.4 % and 80.1 %, respectively.

7. The prototype exhibited Missing indexes of 11.2 %, 23.4 % and 42.8 % for wheat seeds at 4, 6 and 8 km/h, respectively. For sugar beet it exhibited Missing indexes of 8.6 %, 11.6 % and 18.8 %, respectively.

8. The prototype exhibited Multiple indexes of 0 %, 2.3 % and 1.6 % for wheat seeds at 4, 6 and 8 km/h respectively. For sugar beet it exhibited Multiple indexes of 0 %, 0 % and 1.0 %, respectively.

9. The prototype exhibited Precision values of 12.4 %, 12.3 % and 14.1 % for wheat seeds at 4, 6 and 8 km/h respectively. For sugar beet it exhibited Precision values of 10.7 %, 13.3 % and 10.2 %, respectively.

10. The prototype produced uniform seed depth for both seeds (wheat and sugar beet) at all speeds tested (4, 6 and 8 km/h), during seed placement evaluation in the soil bin. The coefficient of variation was 13.7 % and the standard error was 4 mm.

11. Seed selection errors and incorrect seed transfers from the seed metering unit into the delivery punches (seed tubes), significantly reduced the prototype's ability to produce equidistant seed spacing.

12. If the prototype had successfully transferred seeds the CP3 values for wheat would have been 88.8 %, 74.3 % and 55.6 % at 4, 6 and 8 km/h, respectively. For sugar beet these figures would have been: 91.4 %, 88.4 % and 80.1 %, respectively.

13. Solving the problem with seed transfer, would make the ability of the punch planter prototype to place seeds in the soil within a 3 cm range only dependent of seed selection. In this case, a seed metering unit capable of achieving 98 % of seed selection with 2 % of double seed selection, for example, would have

produced a CP3 of 96 %. Precision drills commercially available in Europe use seed metering units capable of producing this level of reliability, for pelleted sugar beet seeds.

14. The research objective of measuring seed positions in the field was not achieved, but a significant progress was made. The results show that solution developed has a superior control of the seed path from the seed metering unit into the soil.

15. The precision punch planter prototype exhibited potential to produce equidistant seed spacing and measure seed locations in the soil of regular and irregular shaped seeds.

9. Recommendations for future research

Recommendations for redesigning the precision punch planter prototype were given in Chapter 7. Following, recommendations and suggestions are given for the application of the precision drilling technology developed.

1. The results encourage designing future prototypes for speeds higher than 8 km/h. For sugar beet the results encourage designing a specialist drill for up to 18 km/h and seed selection is not going to be a problem. Seed selection for wheat and irregular shaped seeds are more difficult to be executed at high speeds, but a good performance might be achieved up to 12 km/h further developing the vacuum operated seed metering unit.

2. A precision drill with multiple rows could be developed to produce an equidistant seed spacing pattern in all directions. Drill units could be synchronized mechanically or hydraulically, using belt drive transmission systems or hydraulic motors, for example. The mechanism shown in figure 9.1 is suggested to continuously vary the position of every drill unit on the chassis while keeping an equidistant drill unit spacing.

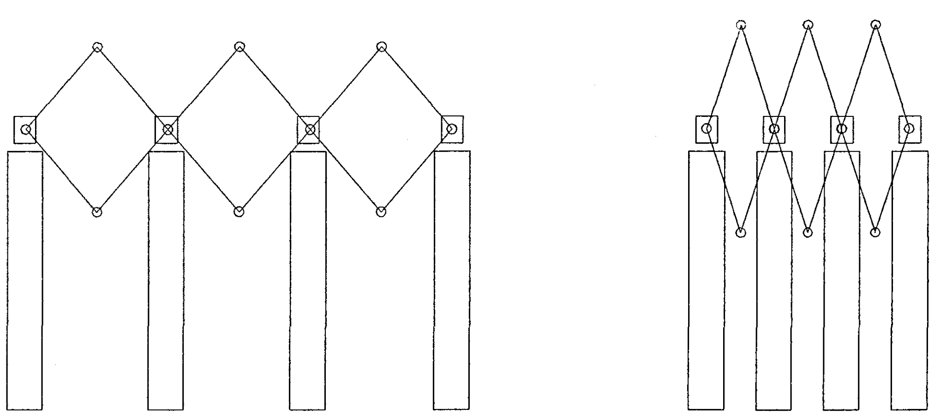


Figure 9.1: Mechanism to vary row spacing keeping an equidistant drill unit spacing

3. Create seed maps for precision agriculture applications at plant-scale level, measuring seed locations in the field. Real-Time-Kinematics GPS could be used

for machine location, a rotational position sensor for punch wheel position and an opto-electronic sensor, placed inside the seed metering unit, for seed detection. The problem with incorrect seed deliveries exhibited by the prototype must be solved to accomplish this task and high speed data logging equipment will be required.

4. The technology developed could be used for minimum tillage and direct drilling systems. The punches penetrate the residue cover and the soil from top to bottom opening the holes in the soil from centre to edge. This combination of movements can avoid dragging residue into the holes therefore seeds can be internally delivered into these holes guaranteeing good seed soil contact. For the same reasons, this solution could be used for plastic mulch systems. For these applications, the use of drills specially designed for specific crops might be an interesting solution to investigate.

5. The double punch wheel concept could be used to develop a combined precision drill to precisely place seeds and fertilizer at optimum distance apart. This development might be incorporated using one or more double punch wheel mechanisms. One punch wheel could incorporate the seed metering unit and the other could incorporate the fertilizer metering unit creating one double punch wheel mechanism capable of distributing seeds and fertilizer. Two double punch wheel mechanisms specifically designed for seeds or for fertilizer might also be used.

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Appendix A

Overview of the development of punch planters

Table A1 shows an overview of the development of punch planters. The author list for these developments is shown below.

1. Jafari, J.V. and Fornstrom, K.J. (1972).
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10. Adekoya, L.O. and Buchele, W.F. (1987.
11. Shaw, L.N. and Kromer, K.H. (1987.
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Table A1: overview of the development of punch planters.

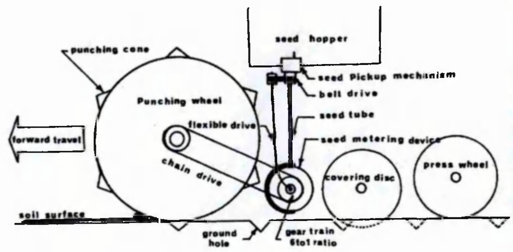
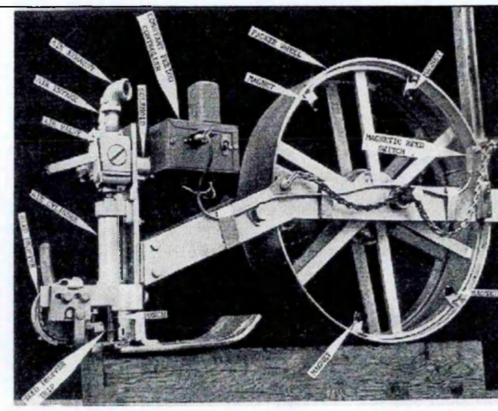
Picture		
General information	Punch planter: #1 Reference: 1 Punch motion: Rotational Punch shape: 6 cones Hole opening: Compression Hole shape: Almost conical Crop type: Sugar beet Seed meter: 2 external units: Pickup & meter, Mechanical, Zero horiz. Speed Seed delivery: External Seed placement: Gravitational Seed spacing: 33 cm - 13"(fixed) Novel: Punch planters	Punch planter: #2 Reference: 2 Punch motion: Linear (only one) Punch shape: 1 cylinder Hole opening: Compression Hole shape: elongated cylinder Crop type: Sugar beet Seed meter: Ratchet driven, Mechanical, Wheel with slots Seed delivery: External Seed placement: Gravitational Seed spacing: Variable Novel: Linear punch, Var. seed spacing
Advantages	Uniform seed-spacing Uniform seed-depth Eliminate seed skips and non-singles Prevent seed damage Working speed 1.34 m/s (4.8 kph) Better seed environment helps to reduce seeding rate Horizontal seed speed in relation to the ground is zero	Seed spacing easily adjusted by changing the position of magnets attached to the packing wheel Uncovered and deeper holes were used to achieve a better germination
Disadvantages	Clogging problems with seed tube that has to deliver a single row of seeds Soil compaction bellow seeds Difficult to vary seed spacing Punch wheel slips if just a few punches are used Punch wheel not power driven	Poor seed delivery Difficult synchronisation Uniform ground speed was a critical factor for seed delivery Many adjustments needed for matching seed delivery time to travel speed Can't open circular holes
Observations	Refine the metering system to eliminate the seed-sizing constraint The seeds were not covered with soil Germination and emergence were not investigated	Improve seed delivery Develop a seed tape to increase its ground speed and the accuracy of seed placement Seeds were not covered Could change depth Separate punch and meter

Table A1: overview of the development of punch planters.

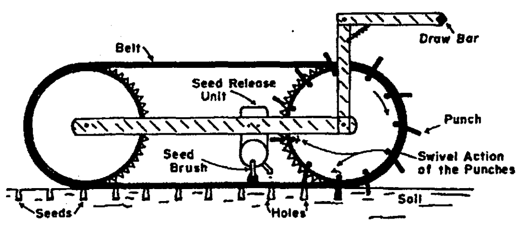
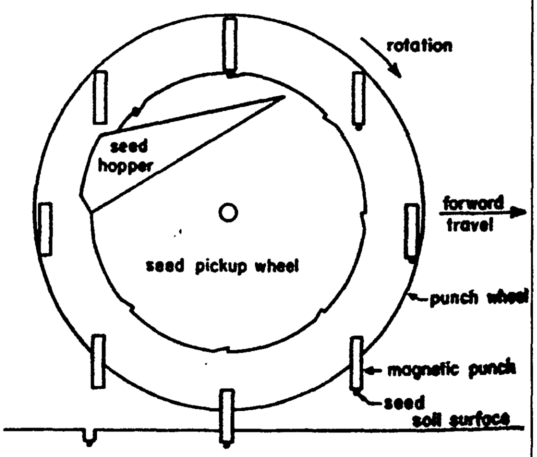
Picture		
General information	Punch planter: #3 Reference: 2 Punch motion: Rotational Punch shape: Cylinder Hole opening: Compression Hole shape: Bell shaped Crop type: Sugar beet Seed meter: Mechanical Wheel with slots Seed delivery: External Seed placement: Dropped over belt Brushed into holes Seed spacing: Fixed Novel: Punching system Seed placement	Punch planter: #4 Reference: 3 Punch motion: Translation Punch shape: Cylinder Hole opening: Compression Hole shape: Cylinder Crop type: Lettuce Seed meter: Mechanical Notched wheel Seed delivery: External Seed placement: Magnetic punches Seed spacing: Fixed Novel: Magnetic seed pickup Seed placement
Advantages	Uniform seed spacing Uncovered holes for better germination Good hole shape Uniform seed depth Good reference for depth measurement	Seeds were placed deeper in the soil and not covered for better germination and emergence Produce a more desirable environment for the developing seedlings Two units were timed to stagger plants
Disadvantages	Needs a uniform moisten soil to make stable hole walls Tendency of the belt to creep with respect of the soil surface making seed delivery impossible Difficult to vary seeding depth Difficult to vary seed spacing	Seeds need to have a magnetically attractive coating Operating speed and magnetically attractive material affected accuracy Some missing seeds Soil moisture content affected the form of the holes Difficult to vary seeding rate
Observations	To design a lower fiction and higher traction belt Use hollow punches and vacuum to pick up seeds and pressurised air for ejection inside hole It seems that the authors didn't build this machine	Optimise geometry of seed wheel Optimise size, shape and depth of punched holes Optimise the coating material Investigate the use for other crops other than lettuce

Table A1: overview of the development of punch planters.

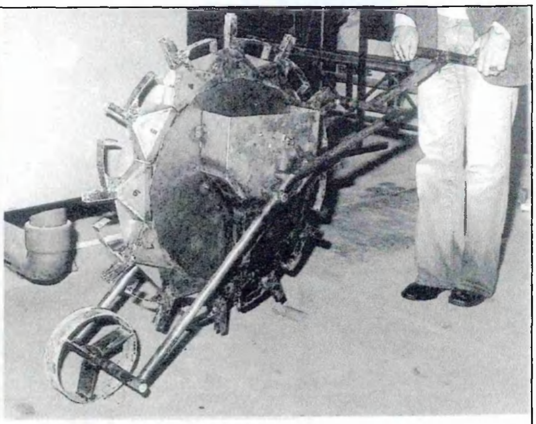
Picture		
General information	Punch planter: #5 Reference: 4 Punch motion: Rotational Punch shape: 5 hollow wedges Hole opening: Jaw mechanism Ground actuated Hole shape: Almost cuboid Crop type: Maize and others Seed meter: Internal unit Mechanical Seed delivery: Internal Seed placement: Gravitational Seed spacing: Fixed Novel: Jaw mechanism Int. seed delivery	Punch planter: #6 Reference: 4 Punch motion: Rotational Punch shape: 12 hollow wedges Hole opening: Jaw mechanism Ground actuated Hole shape: Cuboid Crop type: Maize and others Seed meter: Internal unit Attached to wheel Mechanical Seed delivery: Internal Seed placement: Gravitational Seed spacing: Variab. ± punches Novel: Punch cleaner
Advanta	The machine is cheap Relatively simple Plant through plastic mulch Seed delivery inside punches	Variable seed spacing Good soil penetration
Disadvantage	Clogging problems Fixed seed spacing Seed damage Seed delivery problems Adequate only for walking speeds because it starts to bounce at higher speeds	Poor performance Too complicated Feeder mechanism didn't work at all Severe punch clogging Injector shape not feasible
Observations	Its performance can hardly be surpassed	It didn't improve the old design (the previous one) Design a simpler planter Compromise between simplicity and cheapness Only incorporate cleaner mechanism if necessary Redesign injector

Table A1: overview of the development of punch planters.

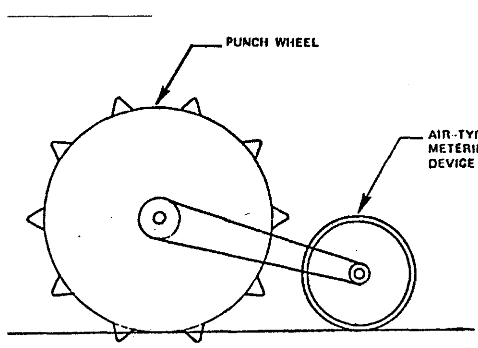
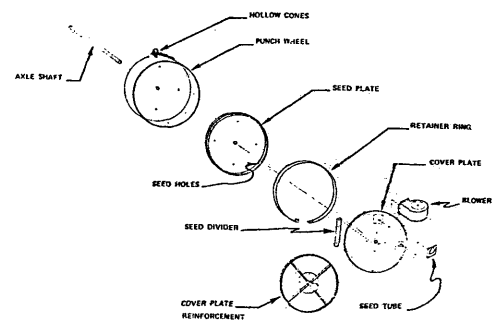
Picture		
General information	Punch planter: #7 Reference: 5 Punch motion: Rotational Punch shape: 10 cones Hole opening: Compression Hole shape: Almost conical Crop type: Navybeans Seed meter: External unit Air type Seed delivery: External Seed placement: Gravitational and air presure Seed spacing: Fixed Novel: Air jet delivery Air type meter	Punch planter: #8 Reference: 5 Punch motion: Rotational Punch shape: Cone – invol. edge Hole opening: Compression and lateral movement Hole shape: Almost conical Crop type: Beans Seed meter: Internal - air type Seed delivery: Internal Seed placement: Gravitational and air presure Seed spacing: Fixed Novel: Air jet delivery Air type meter
Advantages	Accurate seed placement is possible Substitute for furrow openers when excessive surface residue or plastic mulch are used Better seed soil contact	Seed metering unit is inside the punch-wheel Seed delivery using air pressure and centrifugal force Small number of parts (Punch wheel is not inclined) (Simple)
Disadvantages	Uneven cone penetration changed hole spacing making synchronisation with seed metering unit very difficult Separately punching holes and timing a metering device for seed placement has some inherent problems	Negative slip (drag) Clogging problems Problems with seed release timing (seed on the ground) Hole walls collapsed prior to seed placement (loose and dry soils) Faster than ground speed
Observations	This concept was abandoned on early stage of development A similar punch planter was judged good before Similar as #1 but with seed metering and delivery using air pressure	Punch planters requires graded seeds Use aerodynamic and gravitational force to propel seeds to the holes Use positive slip to avoid soil clogging Punch-wheel integrated with seed meter has some definite merits

Table A1: overview of the development of punch planters.

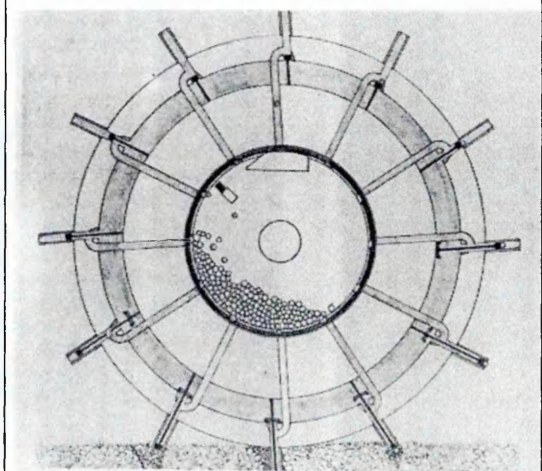
Picture		
General information	Punch planter: #9 Reference: 6 Punch motion: Rotational Punch shape: 6 wollow wedges Hole opening: Jaw mechanism, Ground actuated Hole shape: Almost cuboid Crop type: Maize and others Seed meter: Internal unit, Mechanical Seed delivery: Internal Seed placement: Gravitational Seed spacing: Fixed Novel:	Punch planter: #10 Reference: 7 Punch motion: Rotational Punch shape: 12 hollow cylinders Hole opening: Compression Hole shape: Almost pyramidal Crop type: Seed meter: Internal unit, Mechanical Seed delivery: Internal Seed placement: Mechanical ejector Seed spacing: Fixed Novel: Type of seed delivery and placement
Advantages	Relatively simple Cheap	Relatively simple Suitable for close row spacing
Disadvantages	Problematic seed cut-off Variable planting depth Punch clogging – wet soils Seed metering unit had a poor performance	Difficult to vary seed spacing Seed damage Slide joint close to the soil Clogging problems? Many moving parts Compacted soil under seeds
Observations	Need to be better developed Redesign the injectors to avoid clogging and to facilitate penetrations in dry conditions Choose a better seed metering unit	

Table A1: overview of the development of punch planters.

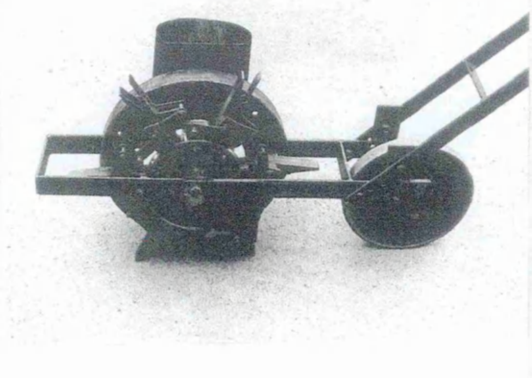
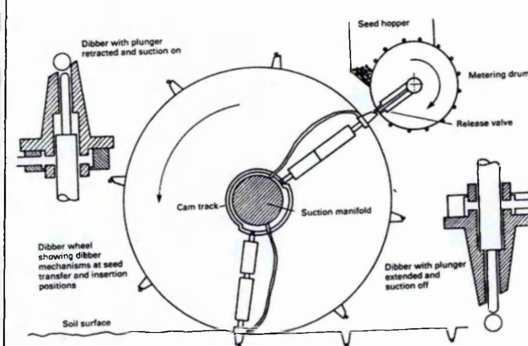
Picture		
General information	Punch planter: #11 Reference: 8 Punch motion: Rotational Punch shape: 6 hollow wedges Hole opening: Jaw mechanism cam actuated Hole shape: Almost cuboid Crop type: Maize and others Seed meter: Internal unit Mechanical Seed delivery: Internal Seed placement: Gravitational Seed spacing: Fixed Novel: Cam actuaded jaw mechanism	Punch planter: #12 Reference: 9 Punch motion: Rotational Punch shape: 8 truncated cones Hollow - ejectors Hole opening: Compression Hole shape: Almost conical Crop type: Pelleted sugarbeet, Lettuce & brassica Seed meter: External - air type Seed delivery: External Punch tip - vacuum Seed placement: Vaccum cut off Seed spacing: Fixed - 150 mm Novel: Vacuum placement
Advantages	Relatively simple Cheap	Very accurate seed spacing Equidistant seed spacing Seed positions are known Simplified seed bed preparation minimise erosion and allow earlier drilling
Disadvantages	Maximum speed of 0.4 m/s Poor penetration - no-tillage Unburied seeds - no-tillage Difficult to work in loose soils Seed lost and damage Straw got jammed in the cam Little time of cell exposure Long and sinuous seed path Big force changes during punch wheel rotation	Maximum forward speed of 0.5 m/s Seed damage Wheel-skip increased seed spacing Drill has no commercial potential Too many moving parts Very complicated
Observations	Better performance in tillage plots Redesign seed hopper to avoid the use of cut-off Improve the shape of the injector funnels device Modify the opening mechanism to prevent the straw getting jammed	Unsuitable in its present stage of development

Table A1: overview of the development of punch planters.

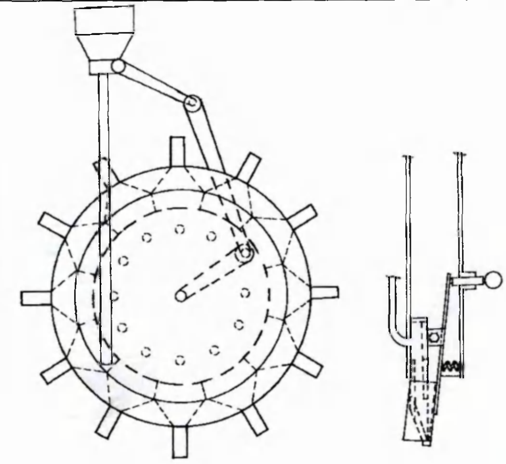
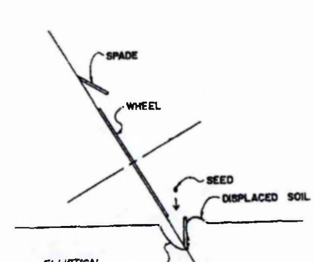
Picture		
General information	Punch planter: #13 Reference: 10 Punch motion: Rotational Punch shape: 12 hollow wedges Hole opening: Jaw mechanism cam actuated Hole shape: Almost cuboid Crop type: Maize and others Seed meter: External Mechanical Seed delivery: Internal Seed placement: Gravitational Seed spacing: Fixed - 255 mm Novel: Orientation of jaw	Punch planter: #14 Reference: 11 Punch motion: Rot. & translation Punch shape: 12 hollow spades Hole opening: Lateral movement Hole shape: Almost cuboid Crop type: Maize Seed meter: Internal Mech. cup-type Seed delivery: Internal Seed placement: Gravitational and centrifugal Seed spacing: Fixed - 180 mm Novel: Opening mech.: Wheel orientation
Advantages	For tilled and untilled soils Good depth control Good seed spacing No clogging problems Performance independent of soil conditions Punch wheel is not inclined	Simple design Cheap to manufacture Easy maintenance Can operate in wet soils Easy punch cleaning
Disadvantage	Seed delivery problems Too many moving parts Long distance between the seed metering unit and the punches Difficult to Lubricate and maintain	Seed delivery problems Maximum speed of 4.5 km/h Non uniform depth at higher speeds Long distance between seed meter and punches (24 cm) Inclined punch wheel generates lateral forces Difficult to be use for short row spacing
Observations	When speed was increased the number of holes with only one seed decreased Some seeds fell on the ground Improve seed delivery	Need to be better tested and developed 

Table A1: overview of the development of punch planters.

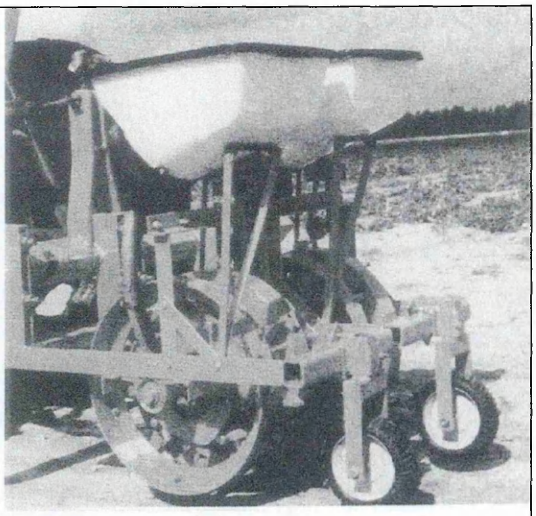
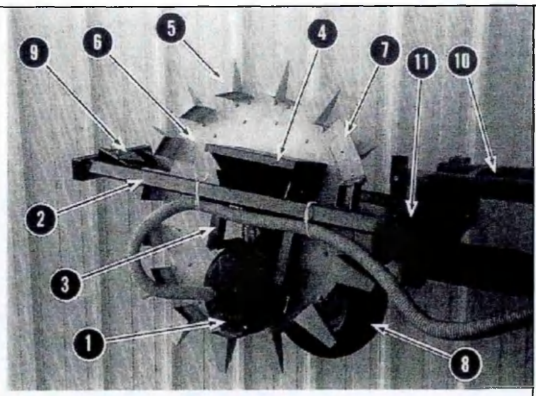
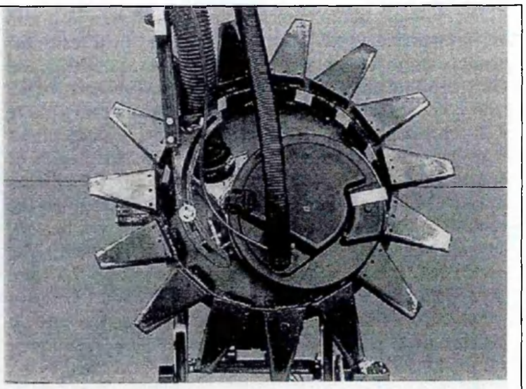
Picture	Not Available	
General information	Punch planter: #15 Reference: 12 Punch motion: Rotational Punch shape: N/A Hole opening: N/A Hole shape: N/A Crop type: Cereals Seed meter: External Seed delivery: Air system Seed placement: N/A Seed spacing: N/A Novel:	Punch planter: #16 Reference: 13 Punch motion: Rotational Punch shape: Hollow wedges Hole opening: Jaw mechanism cam actuated Hole shape: Almost pyramidal Crop type: Vegetables Seed meter: Internal Mechanical Seed delivery: Internal Seed placement: Gravitational Seed spacing: Variable Novel: Mechanism to vary seed-spacing
Advantages	Moisture conservation Improve seed-soil contact Low draft Can work with high amounts of straw above the soil Precise depth control for shallow seeding	Adjustable seed spacing changing the number of punches and cell speed Drill through plastic mulch
Disadvantages	Seed delivery problems	Seed stick inside punches in wet soils or with high amount of residue Many moving parts Difficult to lubricate
Observations	Most seeds were dropped on the soil surface Improve seed delivery The authors didn't explain how the planter works! Bad quality paper	The advantages of plastic mulch culture justify continued punch planter development

Table A1: overview of the development of punch planters.

Picture		
General information	Punch planter: #17 Reference: 14 Punch motion: Rotational Punch shape: 15 hollow prisms Hole opening: Lateral movement Hole shape: Almost cuboid Crop type: Soybean, maize And sugarbeet Seed meter: Internal Vacuum-type Seed delivery: Internal Seed placement: Gravit. & centrif. Seed spacing: Fixed 220 mm Novel: Vacuum meter inside punch wheel	Punch planter: #18 Reference: 15 Punch motion: Rotational Punch shape: 15 hollow prisms Hole opening: Lateral movement Hole shape: Almost cuboid Crop type: Maize Seed meter: Internal Vacuum-type Seed delivery: Internal Seed placement: Gravit. & centrif. Seed spacing: Fixed 136 mm Novel:
Advantages	Uniform seed spacing and depth Favourable environment for the seeds that have a good contact with the soil No furrow to start erosion No trouble with plant residue	Performance not affected by amount and type of residue Good penetration under residue cover Simple
Disadvantages	Limited range of travel speed that it operate satisfactorily	High level of misses Synchronisation problems Unit bounced during field tests Low emergence probably caused by the press wheel Inclined wheel generates lateral forces Difficult to vary seed spacing
Observations	The accuracy of the planter makes it suitable for planting seeds that require high uniformity of in row spacing and depth	

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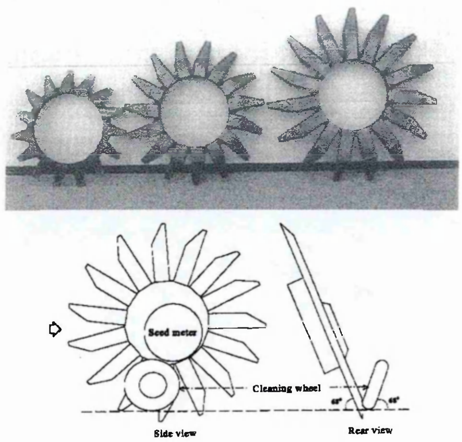
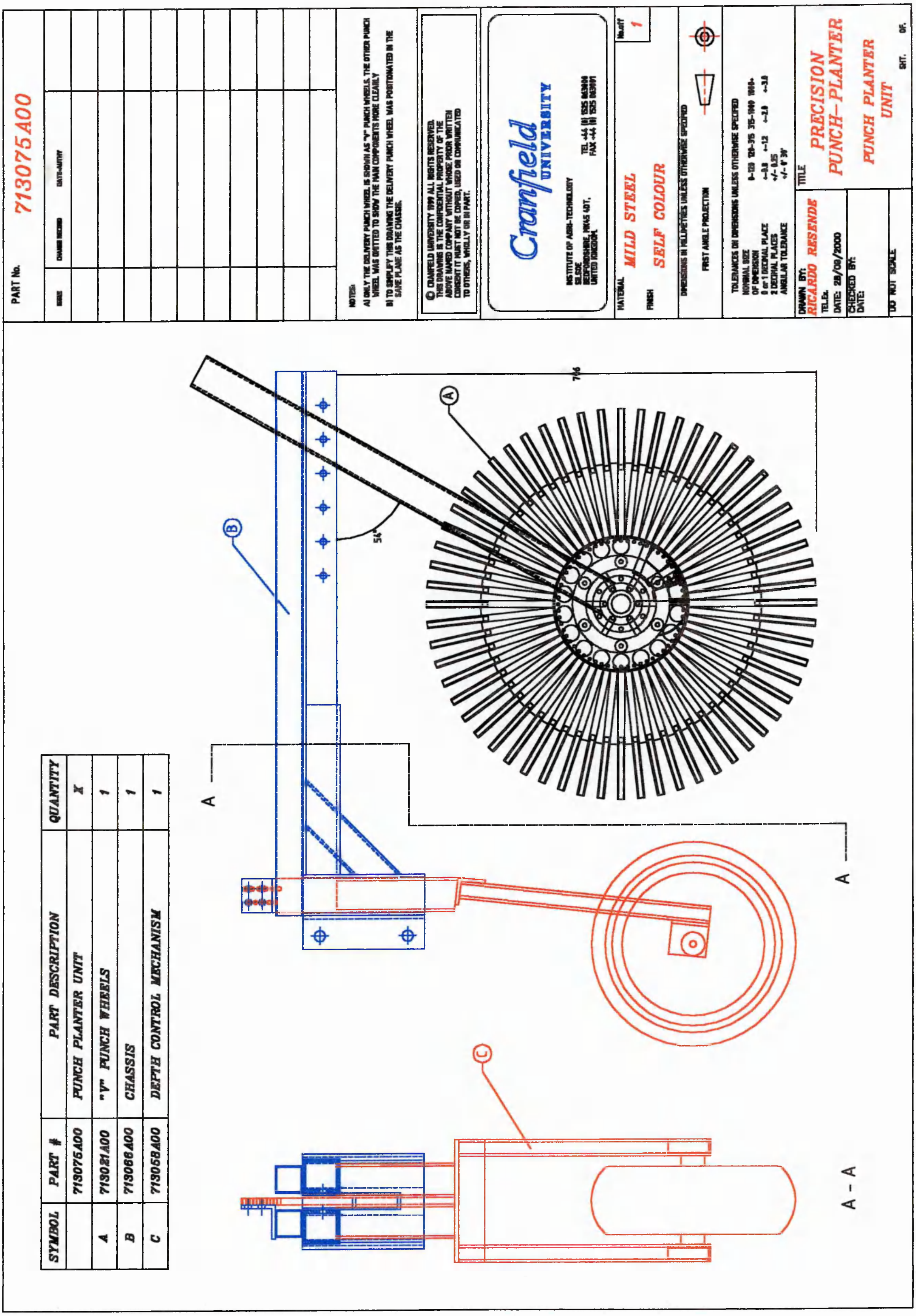
Picture	 	
General information	Punch planter: #19 Reference: 16 Punch motion: Rotational Punch shape: 15 hollow prisms Hole opening: Lateral movement Hole shape: Almost cuboid Crop type: Maize Seed meter: Internal Vacuum-type Seed delivery: Internal Seed placement: Gravit. & centrif. Seed spacing: Variable Novel: Variable seed spacing varying the punch length	
Advantages	Three possible seed spacing using three different punch wheels Reduced soil disturbance Uniform planting depth	
Disadvantages	Synchronisation problems between seed meter and punch wheel Soil sticked on punches Different punch wheel diameters resulted in different timing in the synchronisation between punch wheel and the seed meter	
Observations	Decrease the height of the side doors to prevent seeds from dropping out of the holes Use customised seed meter with the same angular speed as the punches Change the punch wheel diameter to vary seeding rates	

Appendix B

Detailed drawings of the precision punch planter prototype

Contents


SYMBOL | PART # | PART DESCRIPTION | QUANTITY
713075A00 | PUNCH PLANTER UNIT | X
A | 713021A00 | "V" PUNCH WHEELS | 1
B | 713066A00 | CHASSIS | 1
C | 713058A00 | DEPTH CONTROL MECHANISM | 1
A
B
A
54°
C
A - A
PART No. 713075A00
NOTES:
A) ONLY THE DELIVERY PUNCH WHEEL IS SHOWN AS "V" PUNCH WHEELS. THE OTHER PUNCH WHEEL WAS OMITTED TO SHOW THE MAIN COMPONENTS MORE CLEARLY
B) TO SIMPLIFY THIS DRAWING THE DELIVERY PUNCH WHEEL WAS POSITIONATED IN THE SAME PLANE AS THE CHASSIS.
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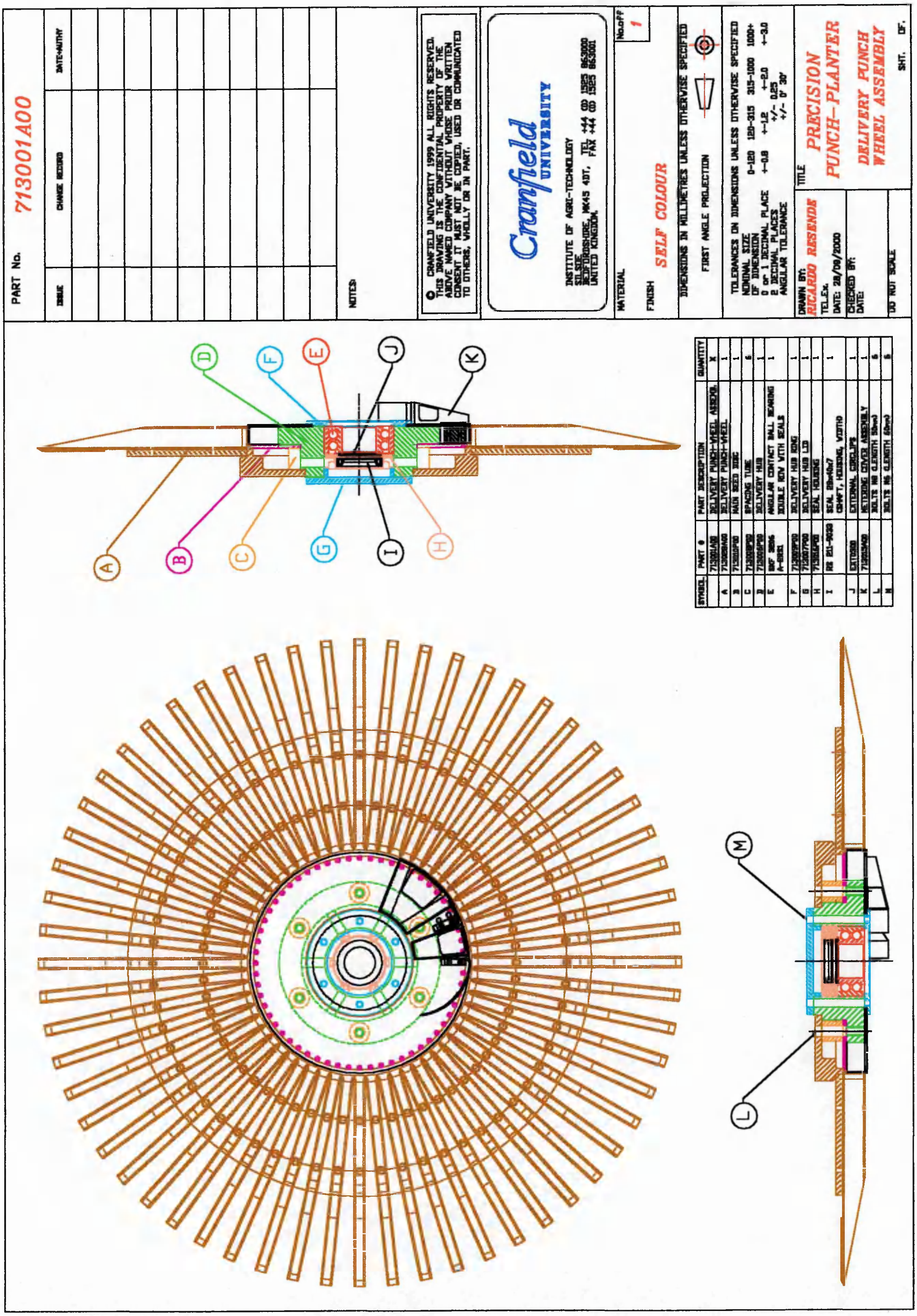
Cranfield UNIVERSITY
INSTITUTE OF AGRI-TECHNOLOGY SILSOE BEDFORDSHIRE, MK45 4DT, UNITED KINGDOM.
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
PUNCH PLANTER UNIT
SHT. OF.


A
B
C
D
E
F
G
H
I
J
K
L
M
SYMBOL | PART # | PART DESCRIPTION | QUANTITY
713001A00 | DELIVERY PUNCH-WHEEL ASSEMBL. | X
A | 713028A00 | DELIVERY PUNCH-WHEEL | 1
B | 713010P00 | MAIN SEED DISC | 1
C | 713008P00 | SPACING TUBE | 6
D | 713006P00 | DELIVERY HUB | 1
E | SKF 3206 A-2RS1 | ANGULAR CONTACT BALL BEARING DOUBLE ROW WITH SEALS | 1
F | 713009P00 | DELIVERY HUB RING | 1
G | 713007P00 | DELIVERY HUB LID | 1
H | 713016P00 | SEAL HOUSING | 1
I | RS 211-9033 | SEAL 28x40x7 (SHAFT, HOUSING, WIDTH) | 1
J | EXT0300 | EXTERNAL CIRCLIPS | 1
K | 713013A00 | METERING COVER ASSEMBLY | 1
L | BOLTS M8 (LENGTH 50mm) | 6
M | BOLTS M6 (LENGTH 60mm) | 6
PART No. 713001A00
ISSUE
CHANGE RECORD
DATE+AUTHY
NOTES:
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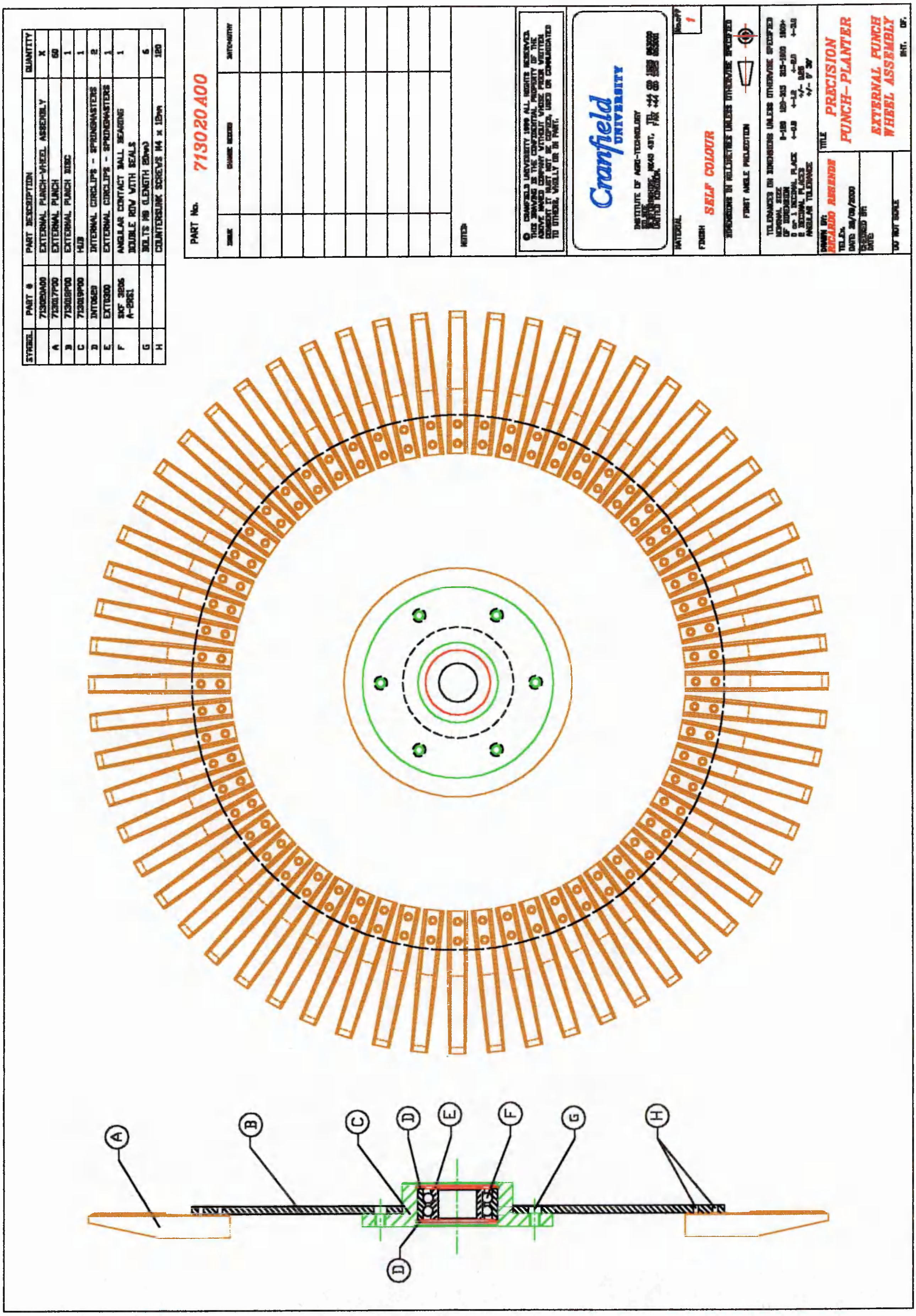
SILSOE
BEDFORDSHIRE, MK45 4DT, TEL +44 (0) 1525 863000
UNITED KINGDOM. FAX +44 (0) 1525 863001
MATERIAL
No.oFF 1
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION 0-120 120-315 315-1000 1000+
0 or 1 DECIMAL PLACE +-0.8 +-1.2 +-2.0 +-3.0
2 DECIMAL PLACES +/- 0.25
ANGULAR TOLERANCE +/- 0° 30'
DRAWN BY: RICARDO RESENDE
TEL.Ex.
DATE: 28/08/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
DELIVERY PUNCH WHEEL ASSEMBLY
SHT. OF.


SYMBOL | PART # | PART DESCRIPTION | QUANTITY
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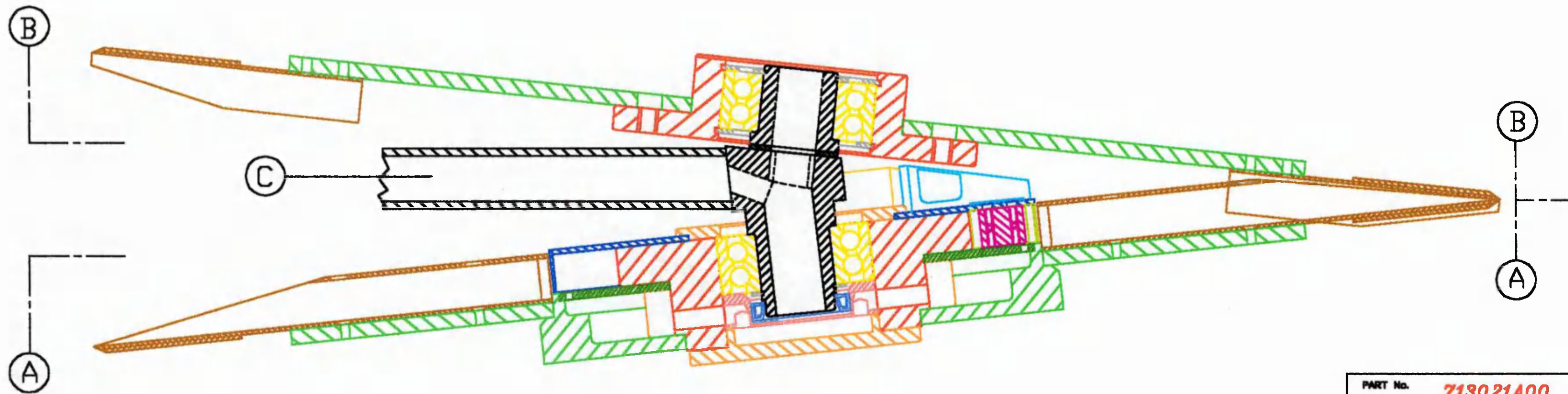
A | 713017P00 | EXTERNAL PUNCH | 60
B | 713018P00 | EXTERNAL PUNCH DISC | 1
C | 713019P00 | HUB | 1
D | INT0620 | INTERNAL CIRCLIPS - SPRINGMASTERS | 2
E | EXT0300 | EXTERNAL CIRCLIPS - SPRINGMASTERS | 1
F | SKF 3206 A-2RS1 | ANGULAR CONTACT BALL BEARING DOUBLE ROW WITH SEALS | 1
G | BOLTS M8 (LENGTH 20mm) | 6
H | COUNTERSUNK SCREWS M4 x 12mm | 120
PART No. 713020A00
NOTES:
Cranfield UNIVERSITY
INSTITUTE OF AGRO-TECHNOLOGY
MATERIAL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE 28/08/2000
TITLE PRECISION PUNCH-PLANTER
EXTERNAL PUNCH WHEEL ASSEMBLY
A
B
C
D
E
F
G
H



SYMBOL	PART #	PART DESCRIPTION	QUANTITY
	713021A00	"V" PUNCH-WHEELS	X
A	713001A00	DELIVERY PUNCH-WHEEL ASSEMBLY	1
B	713020A00	EXTERNAL PUNCH-WHEEL ASSEMBLY	1
C	713030A00	SHAFT ASSEMBLY	1

PART No. 713021A00

NOTES

Cranfield UNIVERSITY

FINISH SELF COLOUR

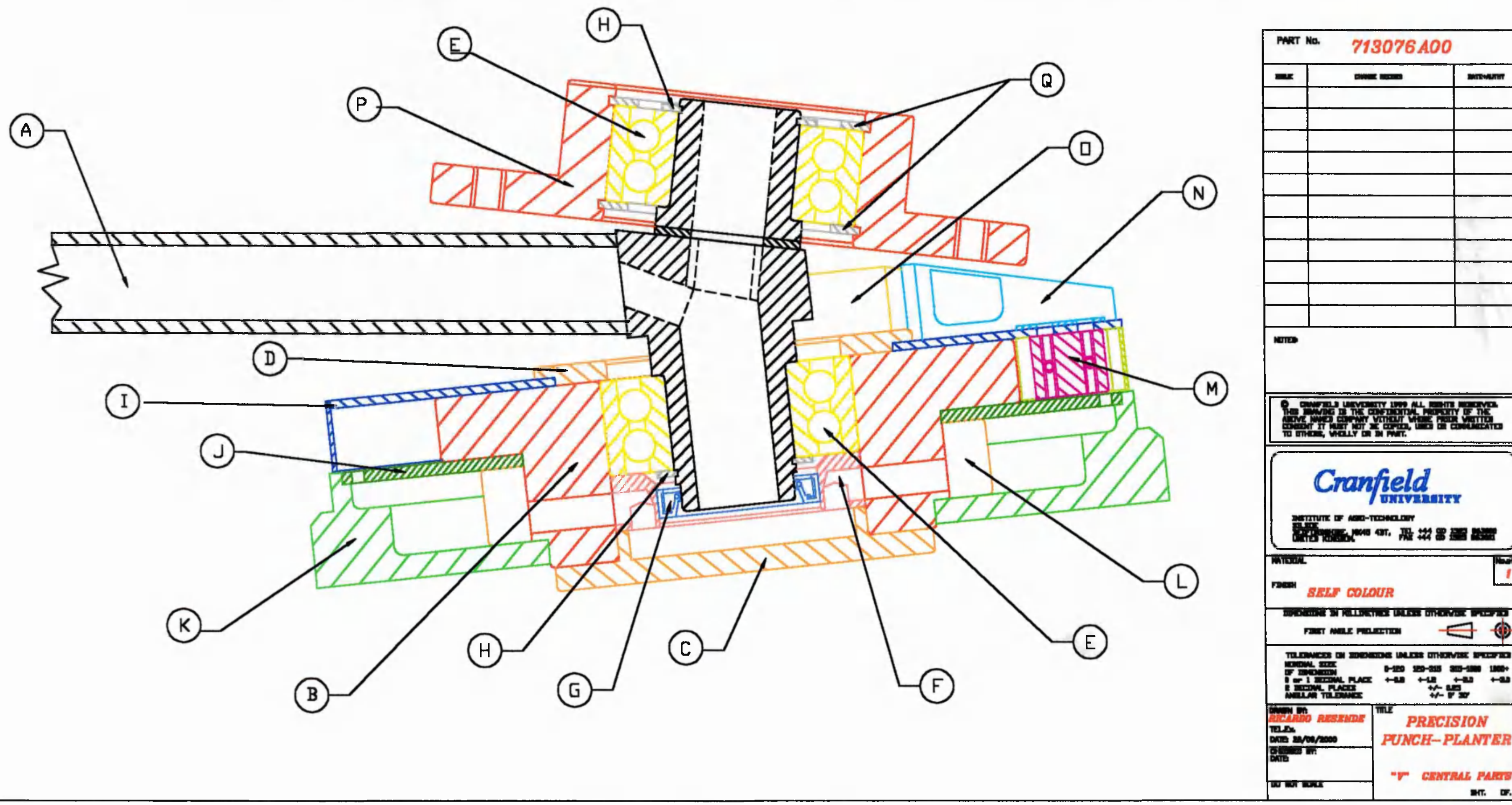
FIRST ANGLE PROJECTION

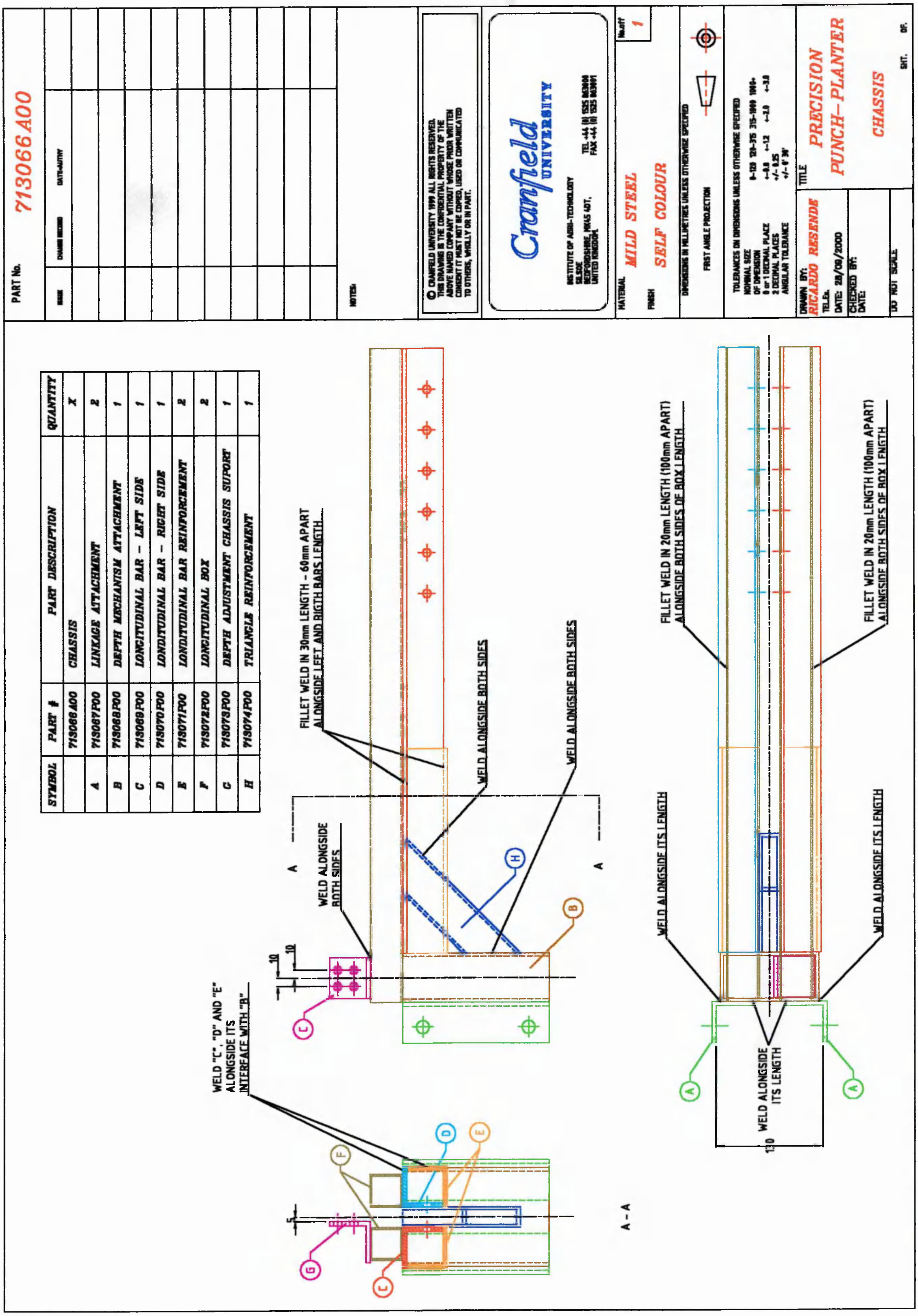
DRAWN BY RICARDO RESENDE

TITLE PRECISION PUNCH-PLANTER "V" PUNCH-WHEELS

SYMBOL	PART #	PART DESCRIPTION	QUANTITY
	713076A00	"V" CENTRAL PARTS	X
A	713030A00	SHAFT ASSEMBLY	1
B	713006P00	DELIVERY HUB	1
C	713007P00	DELIVERY HUB LID	1
D	713009P00	DELIVERY HUB RING	1
E	SKF 3206 A-2RS1	ANGULAR CONTACT BALL BEARING	2
F	713016P00	SEAL HOUSING	1
G	RS 211-9033	SEAL 28x40x7 (SHAFT, HOUSING, WIDTH)	1
H	EXT0300	EXTERNAL CIRCLIPS - SPRINGMASTERS	2

SYMBOL	PART #	PART DESCRIPTION	QUANTITY
I	713015A00	METERING COVER ASSEMBLY	1
J	713010P00	MAIN SEED DISC	1
K	713051P00	DELIVERY PUNCH DISC CENTRE	1
L	713008P00	SPACING TUBE	6
M	713038P00	SEED EJECTOR BASE	1
N	713044P00	AIR INLET	1
O	713043A00	SEED INLET	1
P	713019P00	HUB	1
Q	INT0620	INTERNAL CIRCLIPS - SPRINGMASTERS	2




PART No. 713066 A00
ISSUE
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DATE-AUTHY
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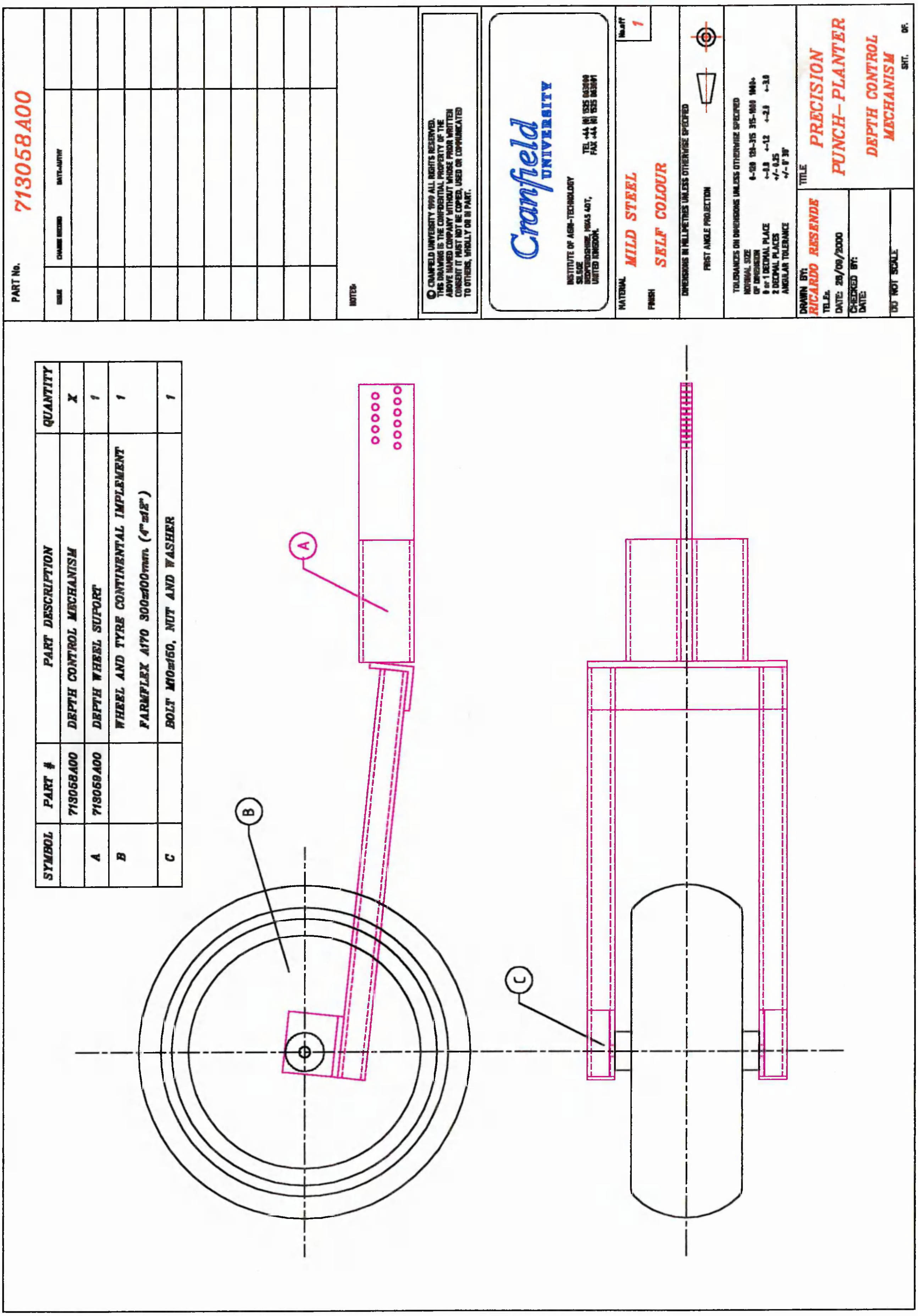
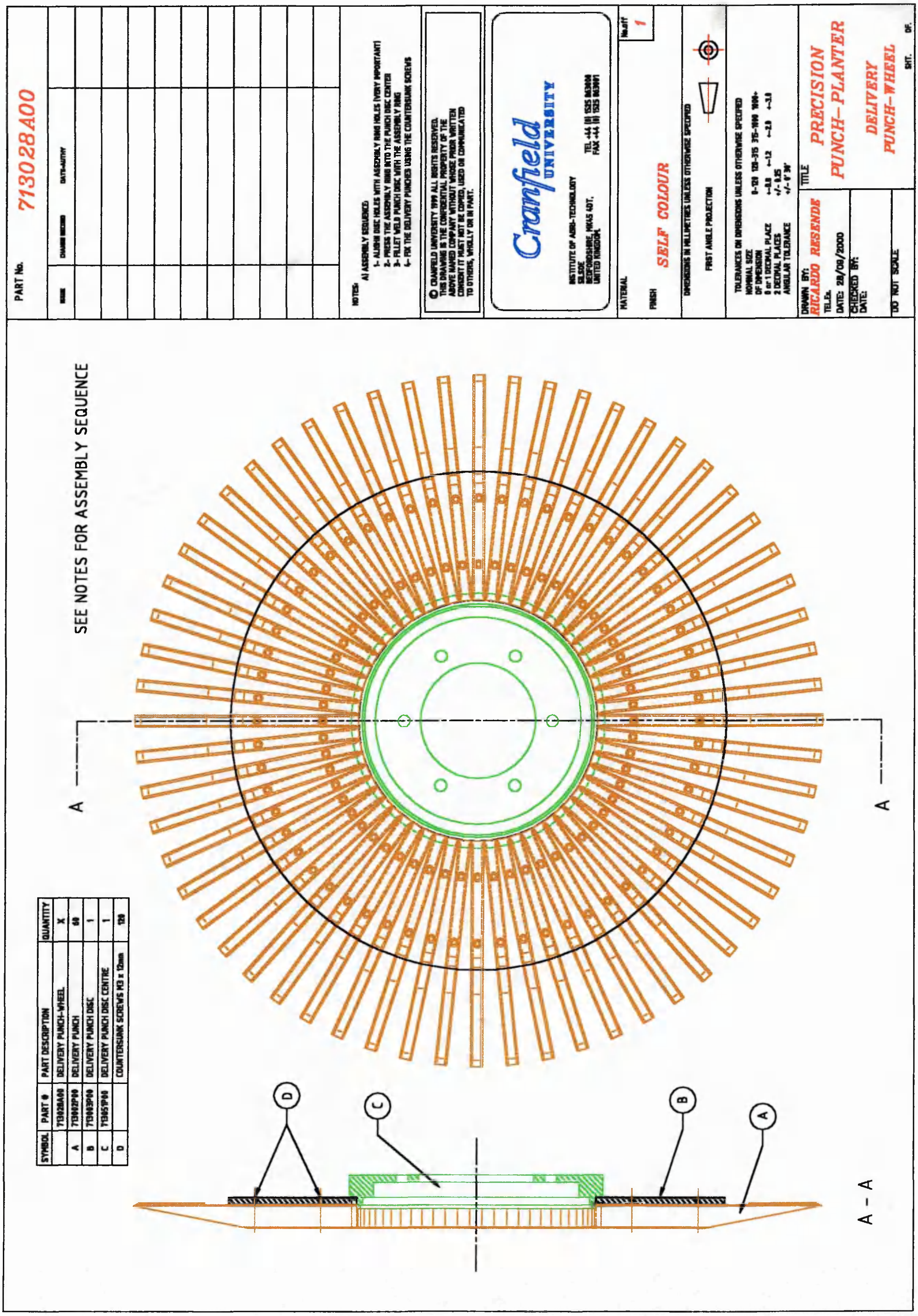
INSTITUTE OF AGRI-TECHNOLOGY
SILSOE
BEDFORDSHIRE, MK45 4DT,
UNITED KINGDOM.
TEL +44 (0) 1525 863000
FAX +44 (0) 1525 863001
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION 0-120 120-315 315-1000 1000+
0 or 1 DECIMAL PLACE +-0.8 +-1.2 +-2.0 +-3.0
2 DECIMAL PLACES +/- 0.25
ANGULAR TOLERANCE +/- 0° 30'
DRAWN BY: RICARDO RESENDE
TEL.Ex.
DATE: 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
CHASSIS
SHT. OF.
SYMBOL | PART # | PART DESCRIPTION | QUANTITY
713066A00 | CHASSIS | X
A | 713067F00 | LINKAGE ATTACHMENT | 2
B | 713068F00 | DEPTH MECHANISM ATTACHMENT | 1
C | 713069F00 | LONGITUDINAL BAR – LEFT SIDE | 1
D | 713070F00 | LONDITUDINAL BAR – RIGHT SIDE | 1
E | 713071F00 | LONDITUDINAL BAR REINFORCEMENT | 2
F | 713072F00 | LONGITUDINAL BOX | 2
G | 713073F00 | DEPTH ADJUSTMENT CHASSIS SUPORT | 1
H | 713074F00 | TRIANGLE REINFORCEMENT | 1
WELD "C", "D" AND "E" ALONGSIDE ITS INTERFACE WITH "B"
WELD ALONGSIDE BOTH SIDES
FILLET WELD IN 30mm LENGTH - 60mm APART ALONGSIDE LEFT AND RIGTH BARS LENGTH
WELD ALONGSIDE BOTH SIDES
WELD ALONGSIDE BOTH SIDES
A – A
WELD ALONGSIDE ITS LENGTH
FILLET WELD IN 20mm LENGTH (100mm APART) ALONGSIDE BOTH SIDES OF BOX LENGTH
WELD ALONGSIDE ITS LENGTH
130
FILLET WELD IN 20mm LENGTH (100mm APART) ALONGSIDE BOTH SIDES OF BOX LENGTH
WELD ALONGSIDE ITS LENGTH


PART No. 713058A00
SYMBOL
PART #
PART DESCRIPTION
QUANTITY
713058A00
DEPTH CONTROL MECHANISM
X
A
713059A00
DEPTH WHEEL SUPORT
1
B
WHEEL AND TYRE CONTINENTAL IMPLEMENT FARMPLEX A170 300x100mm (4"x12")
1
C
BOLT M10x160, NUT AND WASHER
1
A
B
C
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
DEPTH CONTROL MECHANISM


SYMBOL | PART # | PART DESCRIPTION | QUANTITY
713028A00 | DELIVERY PUNCH-WHEEL | X
A | 713002P00 | DELIVERY PUNCH | 60
B | 713003P00 | DELIVERY PUNCH DISC | 1
C | 713051P00 | DELIVERY PUNCH DISC CENTRE | 1
D | COUNTERSUNK SCREWS M3 x 12mm | 120
SEE NOTES FOR ASSEMBLY SEQUENCE
A
A
A - A
D
C
B
A
PART No. 713028A00
ISSUE
CHANGE RECORD
DATE-AUTHY
NOTES:
A) ASSEMBLY SEQUENCE:
1- ALIGN DISC HOLES WITH ASSEMBLY RING HOLES (VERY IMPORTANT)
2- PRESS THE ASSEMBLY RING INTO THE PUNCH DISC CENTER
3- FILLET WELD PUNCH DISC WITH THE ASSEMBLY RING
4- FIX THE DELIVERY PUNCHES USING THE COUNTERSUNK SCREWS
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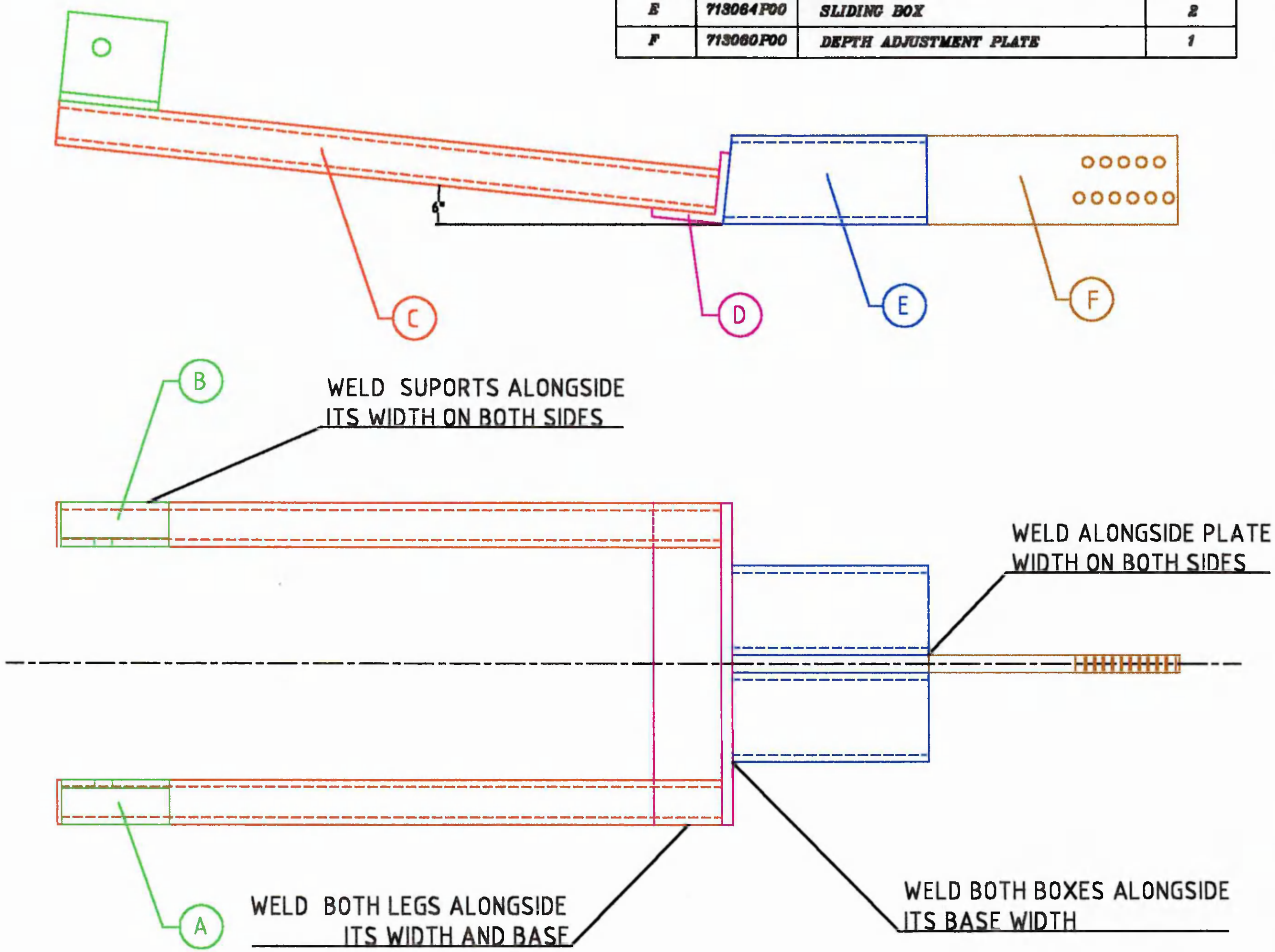
SILSOE
BEDFORDSHIRE, MK45 4DT,
UNITED KINGDOM.
TEL +44 (0) 1525 863000
FAX +44 (0) 1525 863001
MATERIAL
No.off 1
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION 0-120 120-315 315-1000 1000+
0 or 1 DECIMAL PLACE +-0.8 +-1.2 +-2.0 +-3.0
2 DECIMAL PLACES +/- 0.25
ANGULAR TOLERANCE +/- 0° 30'
DRAWN BY: RICARDO RESENDE
TEL.Ex.
DATE: 28/08/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
DELIVERY PUNCH-WHEEL
SHT. OF.

SYMBOL	PART #	PART DESCRIPTION	QUANTITY
	713059A00	DEPTH WHEEL SUPORT	X
A	713061P00	SHAFT SUPORT – LEFT SIDE	1
B	713062P00	SHAFT SUPORT – RIGHT SIDE	1
C	713065P00	LEG	2
D	713063P00	LEG'S BASE	1
E	713064P00	SLIDING BOX	2
F	713060P00	DEPTH ADJUSTMENT PLATE	1



PART No. 713059A00

ISSUE	CHANGE RECORD	DATE-AUTHY

NOTES:

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INSTITUTE OF AGRI-TECHNOLOGY
SILSOE
BEDFORDSHIRE, MK45 4DT,
UNITED KINGDOM.
TEL +44 (0) 1525 863000
FAX +44 (0) 1525 863001

MATERIAL: MILD STEEL
FINISH: SELF COLOUR
No.off: 1

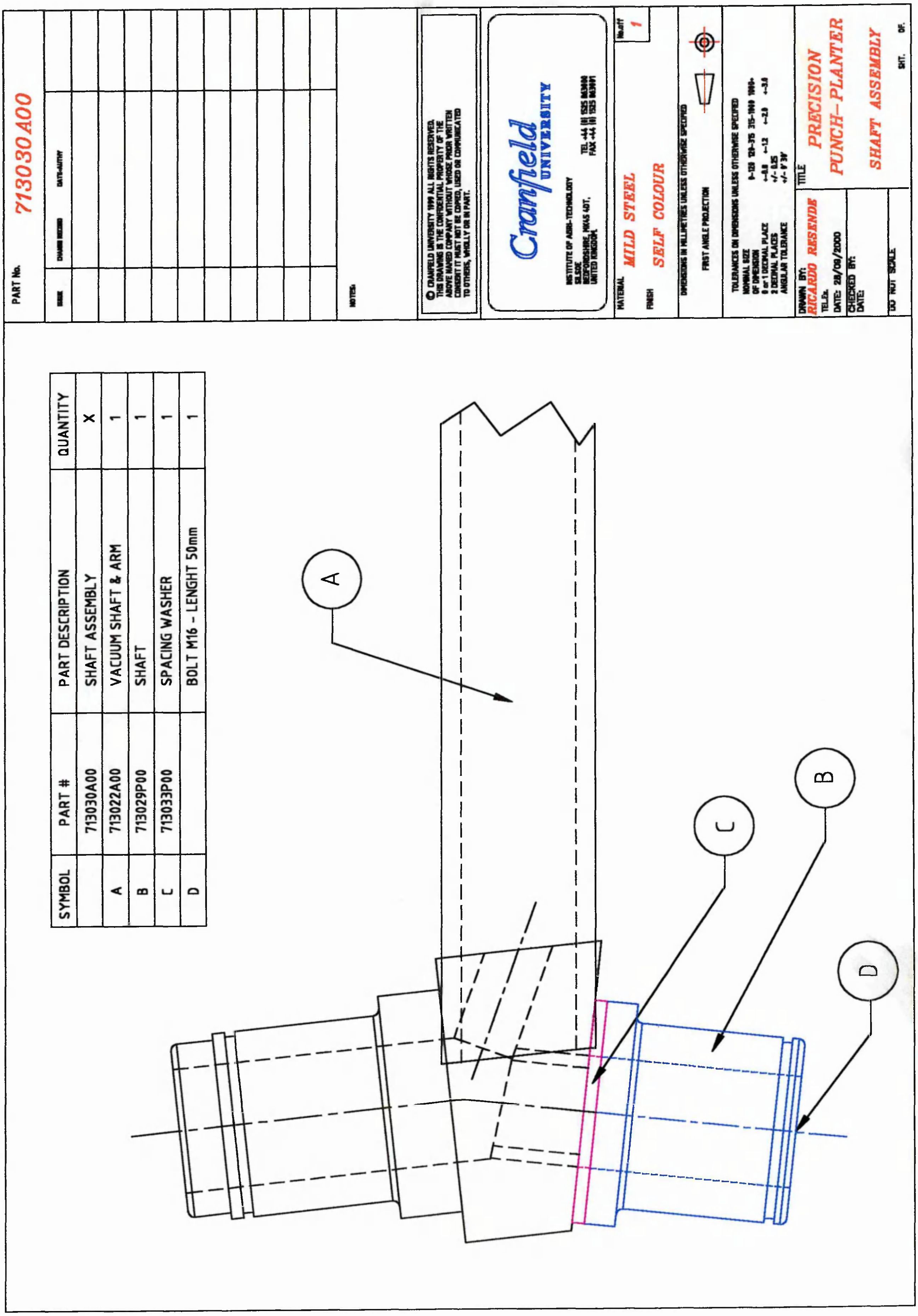
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION

TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED

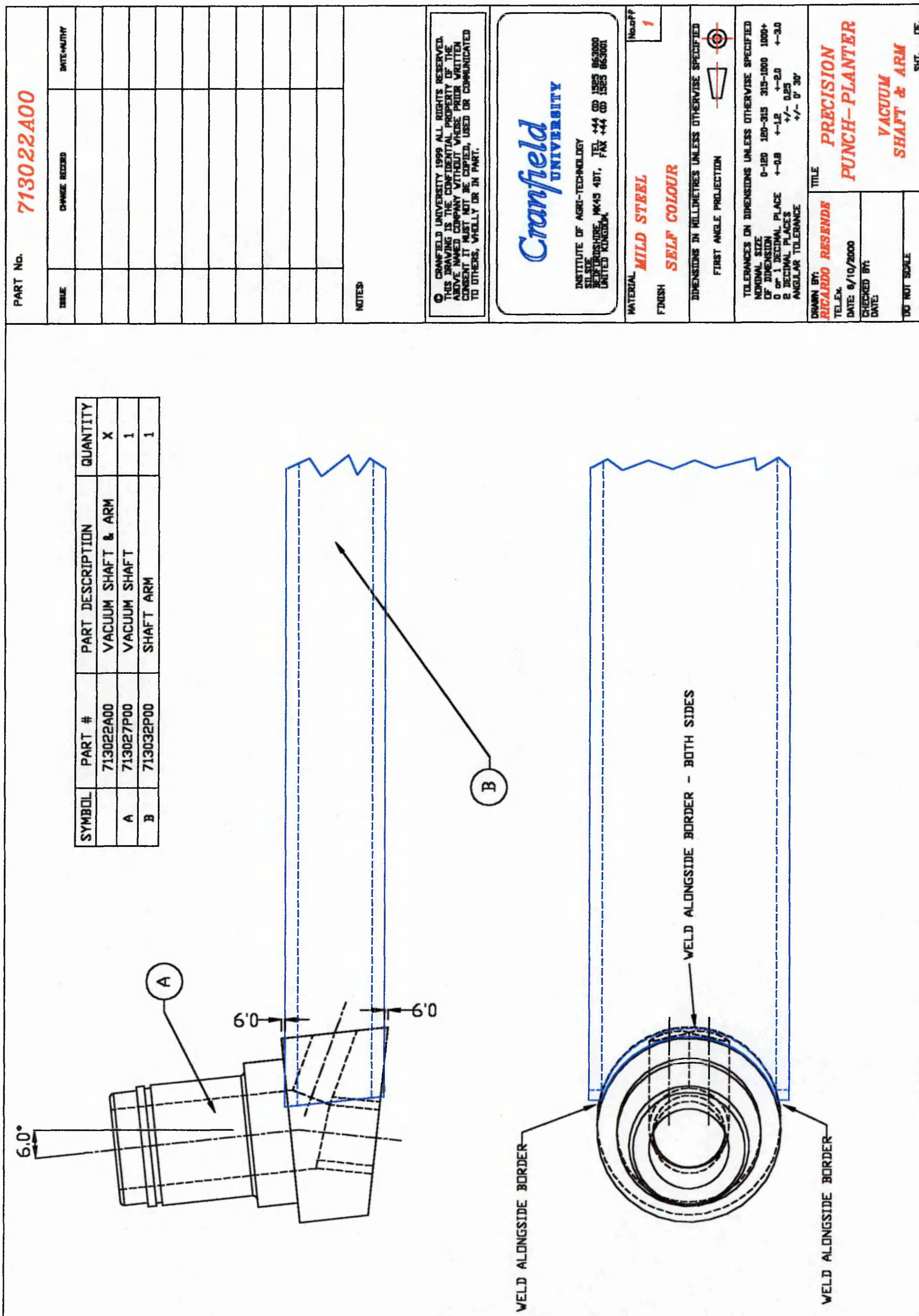
NOMINAL SIZE OF DIMENSION	0-120	120-315	315-1000	1000+
0 or 1 DECIMAL PLACE	+-0.8	+-1.2	+-2.0	+-3.0
2 DECIMAL PLACES	+/- 0.25			
ANGULAR TOLERANCE	+/- 0° 30'			

DRAWN BY: RICARDO RESENDE
TEL.Ex.
DATE: 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE

TITLE: PRECISION PUNCH–PLANTER
DEPTH WHEEL SUPORT
SHT. OF.



SYMBOL	PART #	PART DESCRIPTION	QUANTITY
	713030A00	SHAFT ASSEMBLY	X
A	713022A00	VACUUM SHAFT & ARM	1
B	713029P00	SHAFT	1
C	713033P00	SPACING WASHER	1
D		BOLT M16 - LENGHT 50mm	1



PART No. 713022A00
ISSUE
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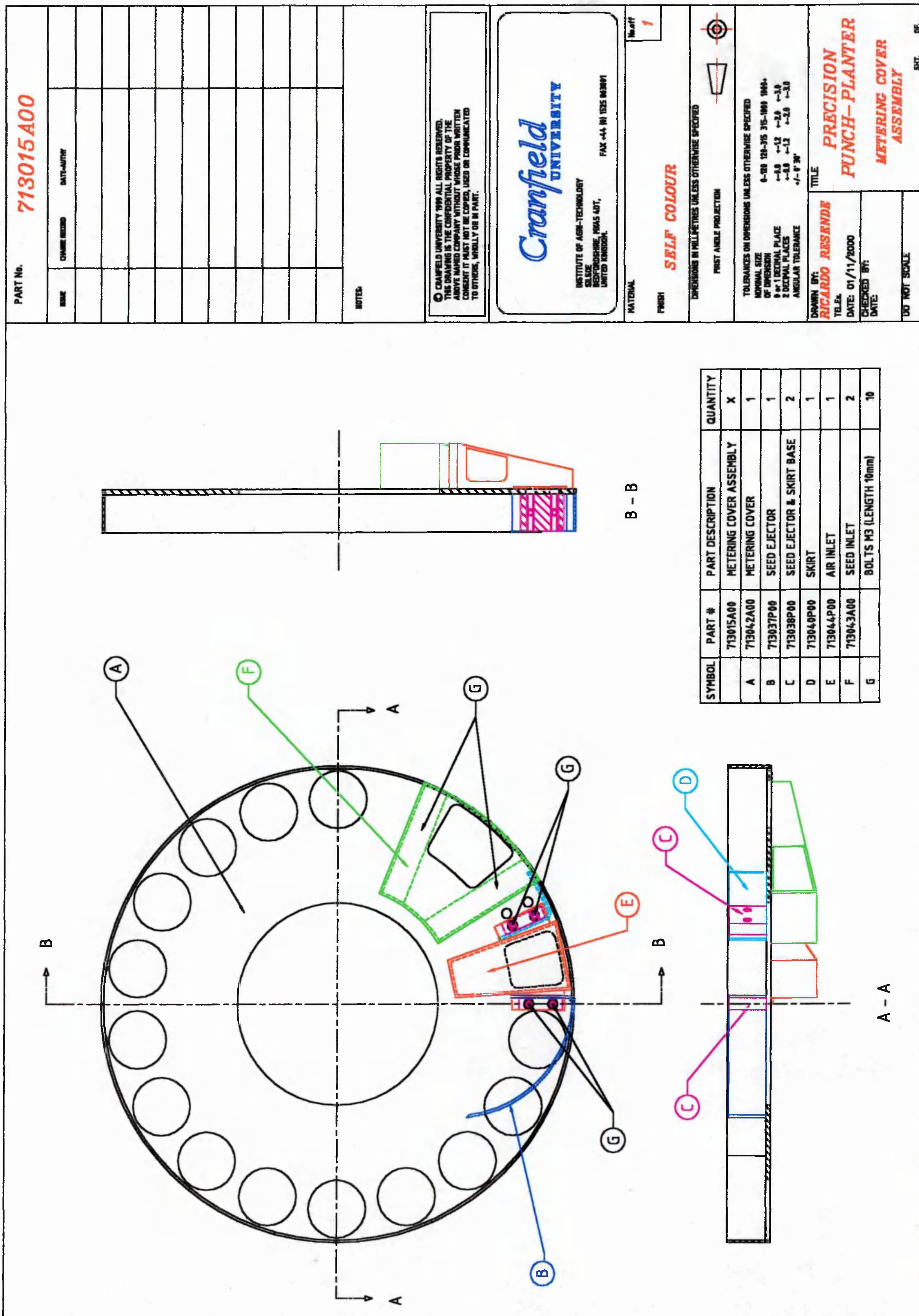
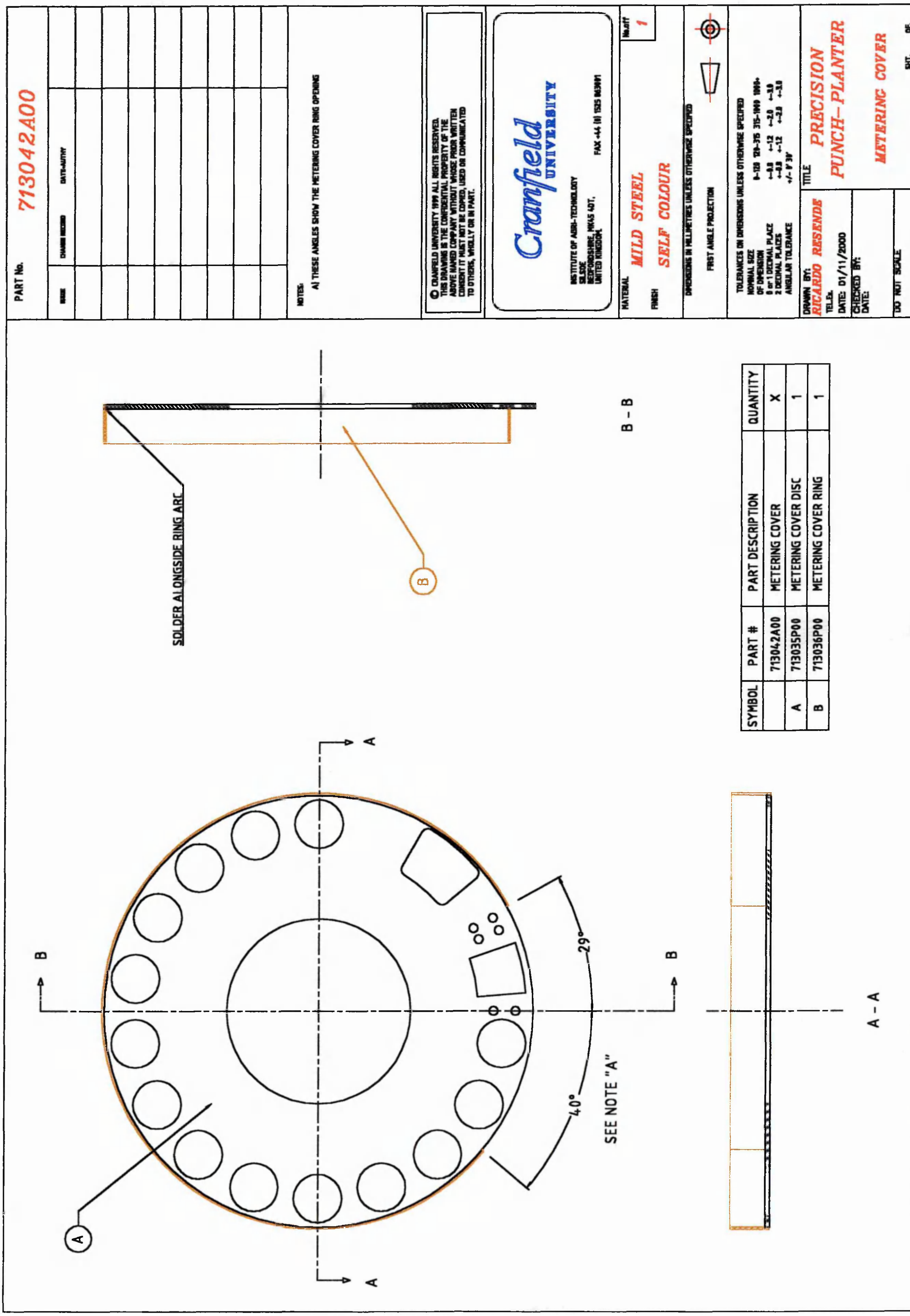
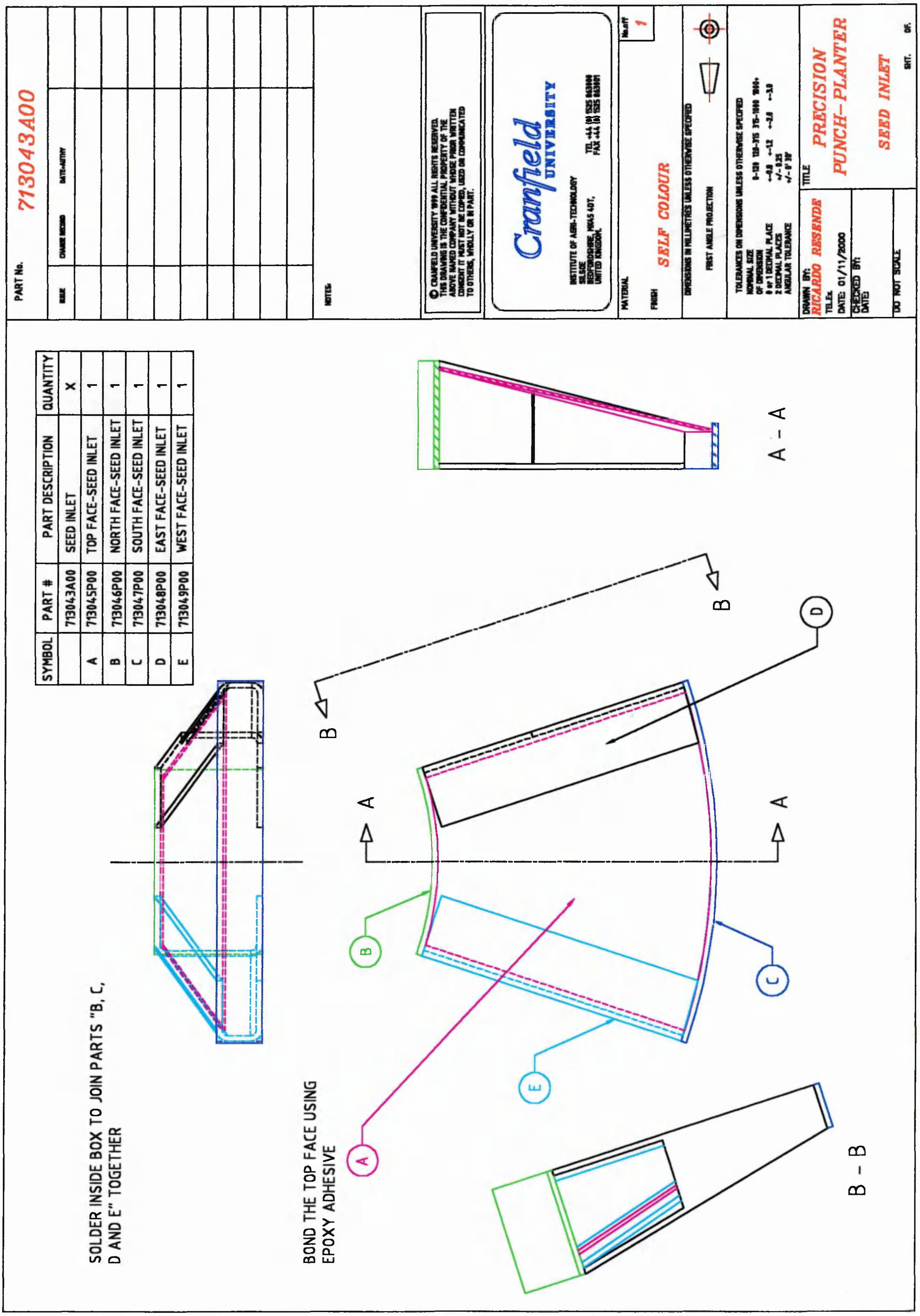
FAX +44 (0) 1525 863001
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.OFF 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION 0-120 120-315 315-1000 1000+
0 or 1 DECIMAL PLACE +-0.8 +-1.2 +-2.0 +-3.0
2 DECIMAL PLACES +/- 0.25
ANGULAR TOLERANCE +/- 0° 30'
DRAWN BY: RICARDO RESENDE
TEL.Ex.
DATE: 6/10/2000
CHECKED BY:
DATE:
TITLE PRECISION PUNCH-PLANTER
VACUUM SHAFT & ARM
DO NOT SCALE
SHT. OF.
SYMBOL | PART # | PART DESCRIPTION | QUANTITY
| 713022A00 | VACUUM SHAFT & ARM | X
A | 713027P00 | VACUUM SHAFT | 1
B | 713032P00 | SHAFT ARM | 1
A
B
6.0°
6'0
6'0
WELD ALONGSIDE BORDER - BOTH SIDES
WELD ALONGSIDE BORDER
WELD ALONGSIDE BORDER



SYMBOL	PART #	PART DESCRIPTION	QUANTITY
	713015A00	METERING COVER ASSEMBLY	X
A	713042A00	METERING COVER	1
B	713037P00	SEED EJECTOR	1
C	713038P00	SEED EJECTOR & SKIRT BASE	2
D	713040P00	SKIRT	1
E	713044P00	AIR INLET	1
F	713043A00	SEED INLET	2
G		BOLTS M3 (LENGTH 10mm)	10



SYMBOL	PART #	PART DESCRIPTION	QUANTITY
	713042A00	METERING COVER	X
A	713035P00	METERING COVER DISC	1
B	713036P00	METERING COVER RING	1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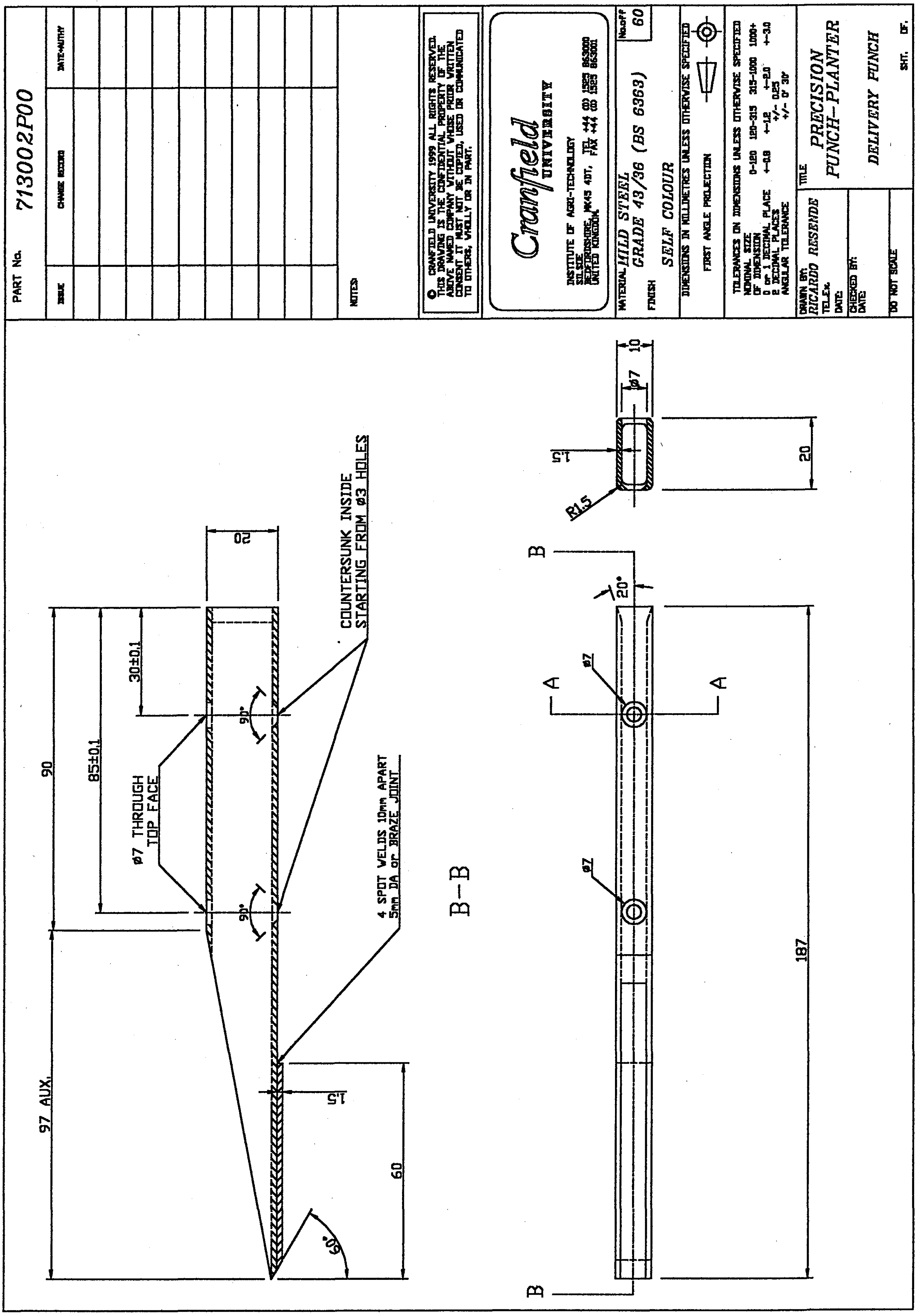
TEL +44 (0) 1525 863000 FAX +44 (0) 1525 863001
No.off 1
MATERIAL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER SEED INLET
SHT. OF.
SYMBOL | PART # | PART DESCRIPTION | QUANTITY
713043A00 | SEED INLET | X
A | 713045P00 | TOP FACE-SEED INLET | 1
B | 713046P00 | NORTH FACE-SEED INLET | 1
C | 713047P00 | SOUTH FACE-SEED INLET | 1
D | 713048P00 | EAST FACE-SEED INLET | 1
E | 713049P00 | WEST FACE-SEED INLET | 1
SOLDER INSIDE BOX TO JOIN PARTS "B, C, D AND E" TOGETHER
BOND THE TOP FACE USING EPOXY ADHESIVE
A - A
B - B
A
B
C
D
E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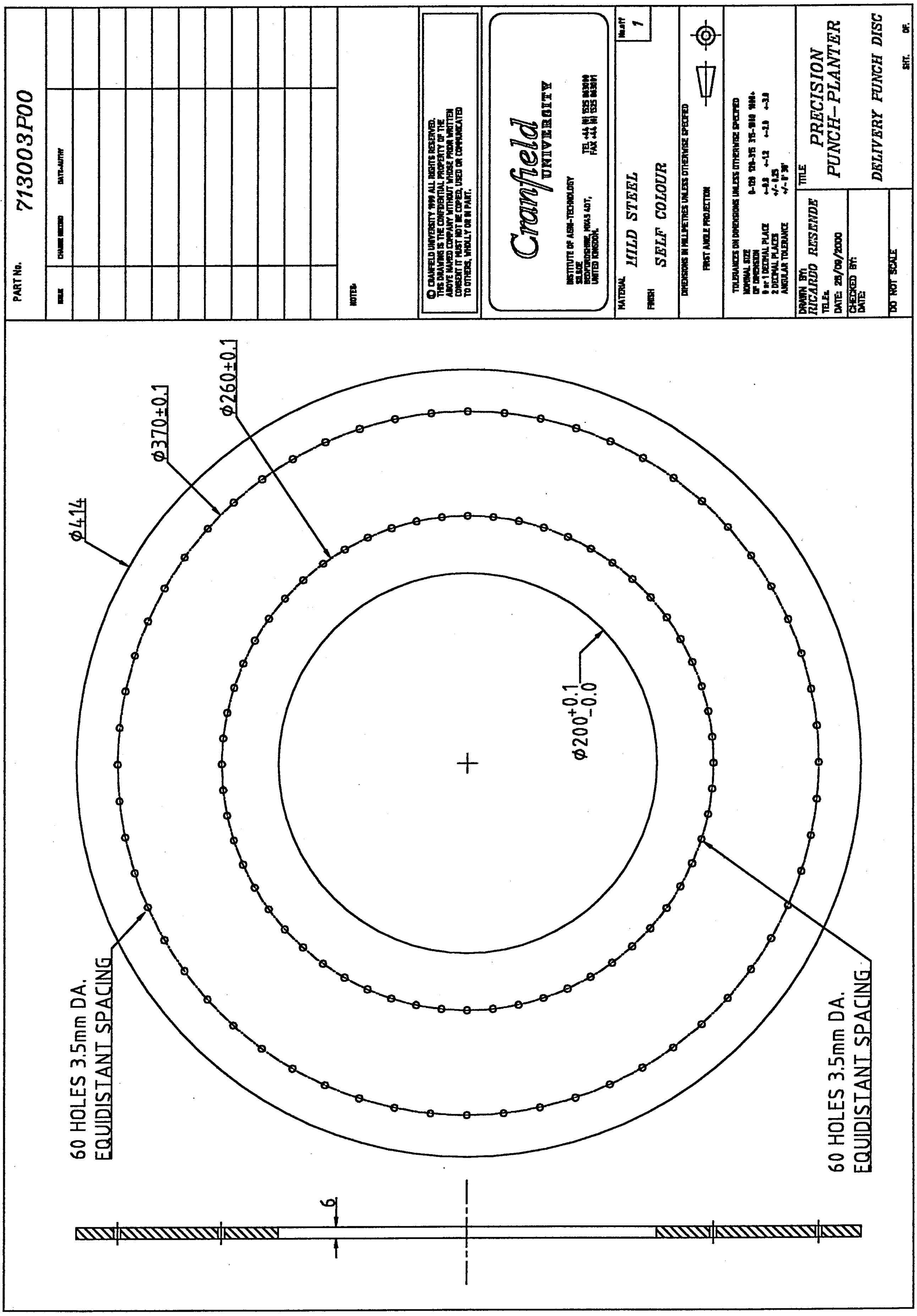
MATERIAL MILD STEEL GRADE 43/36 (BS 6363)
No.off 60
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
DRAWN BY: RICARDO RESENDE
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
DELIVERY PUNCH
SHT. OF.
97 AUX.
90
85±0.1
30±0.1
20
ø7 THROUGH TOP FACE
COUNTERSUNK INSIDE STARTING FROM ø3 HOLES
4 SPOT WELDS 10mm APART 5mm DIA or BRAZE JOINT
B-B
90°
60°
1.5
60
187
20°
ø7
A
B
R1.5
10
ø7
1.5
20


PART No. 713003P00
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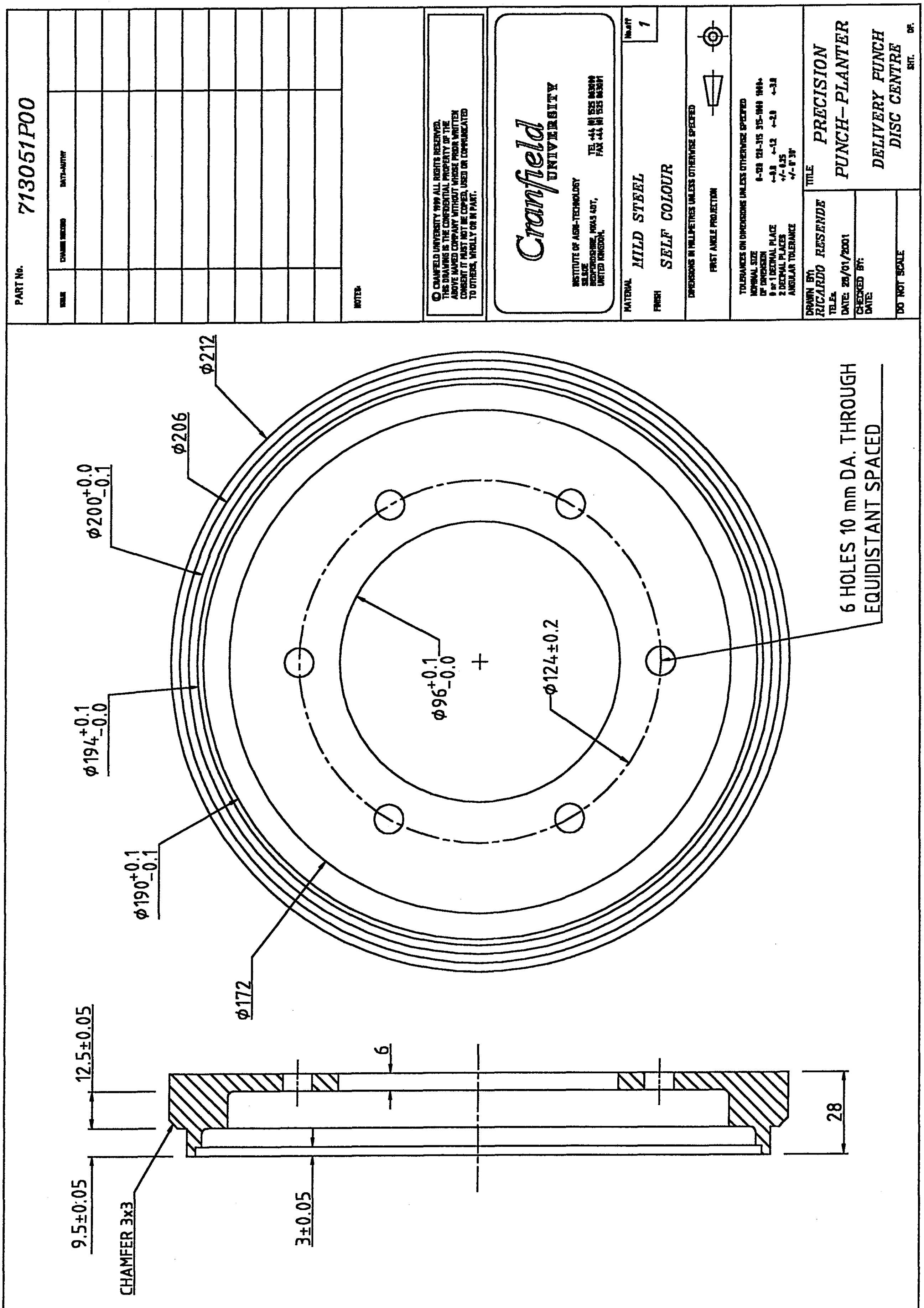
INSTITUTE OF AGRI-TECHNOLOGY
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH–PLANTER
DELIVERY PUNCH DISC
Φ414
Φ370±0.1
Φ260±0.1
Φ200 +0.1 −0.0
60 HOLES 3.5mm DA.
EQUIDISTANT SPACING
60 HOLES 3.5mm DA.
EQUIDISTANT SPACING
6


PART No. 713051P00
NOTES
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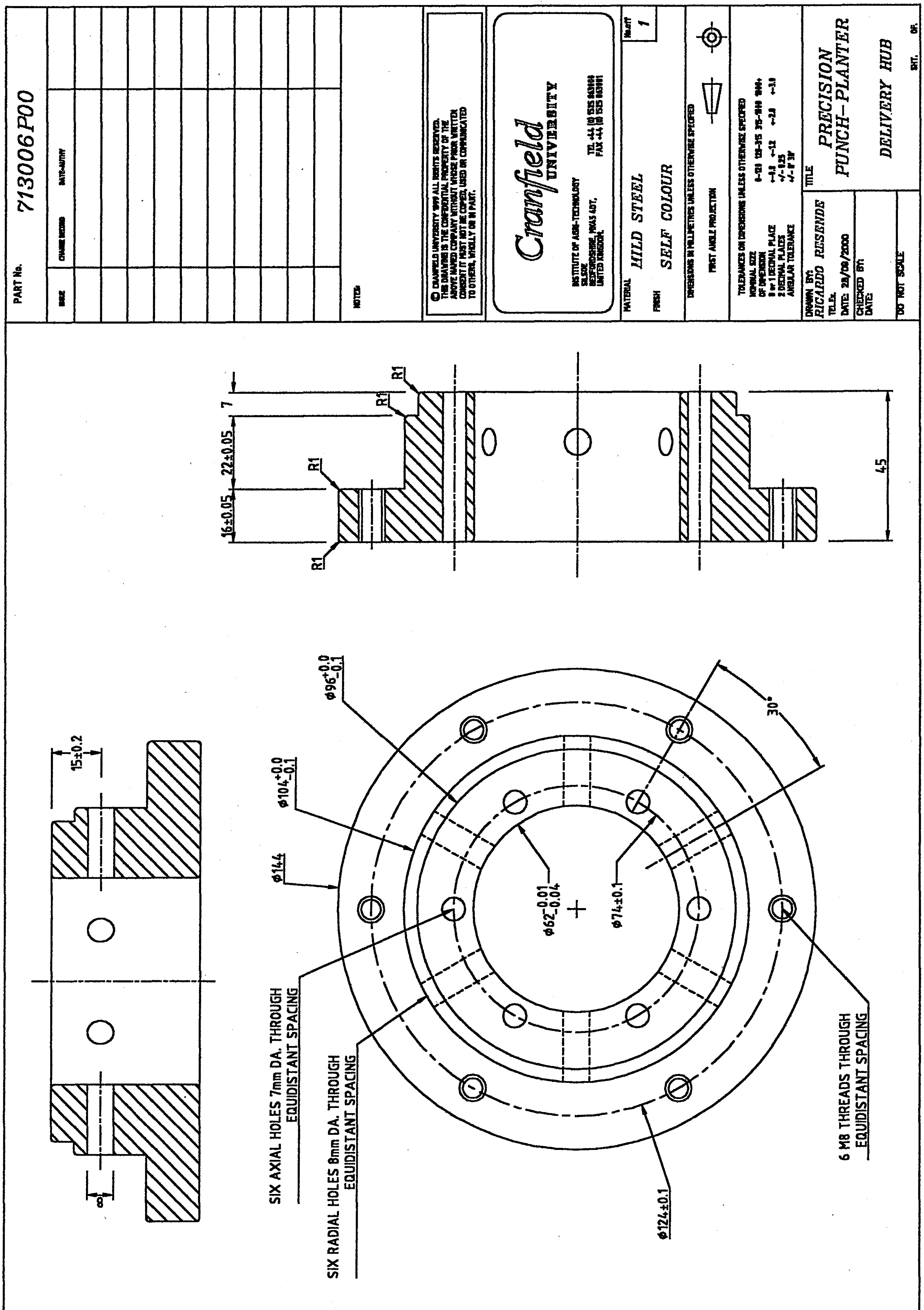
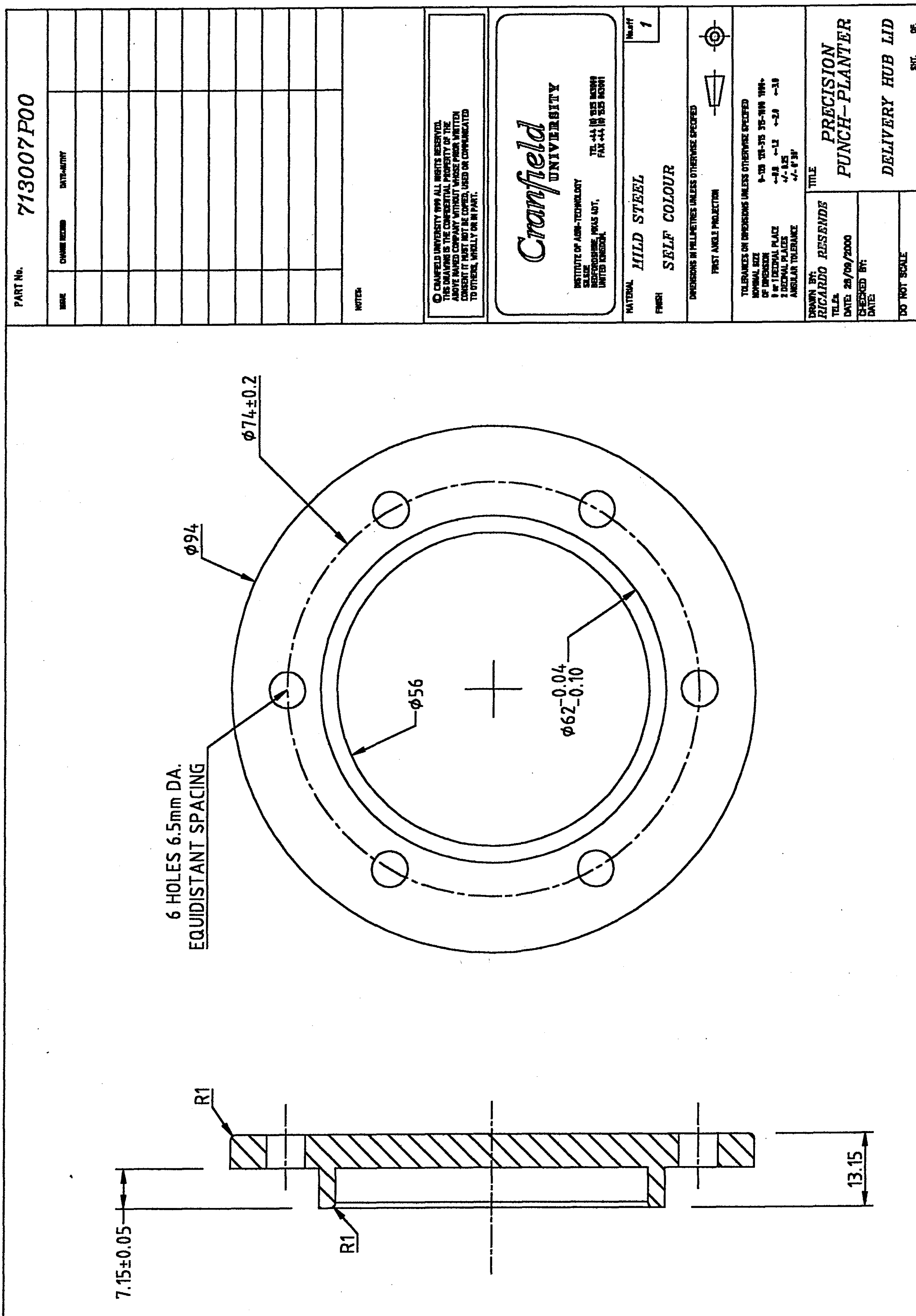
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 25/01/2001
TITLE PRECISION PUNCH-PLANTER
DELIVERY PUNCH DISC CENTRE
DO NOT SCALE
ϕ212
ϕ206
ϕ200 +0.0 −0.1
ϕ194 +0.1 −0.0
ϕ190 +0.1 −0.1
ϕ172
ϕ96 +0.1 −0.0
ϕ124±0.2
6 HOLES 10 mm DA. THROUGH EQUIDISTANT SPACED
12.5±0.05
9.5±0.05
CHAMFER 3x3
3±0.05
6
28


PART No.
713006P00
NOTES
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TITLE PRECISION PUNCH-PLANTER
DELIVERY HUB
DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DO NOT SCALE
SIX AXIAL HOLES 7mm DA. THROUGH EQUIDISTANT SPACING
SIX RADIAL HOLES 8mm DA. THROUGH EQUIDISTANT SPACING
6 M8 THREADS THROUGH EQUIDISTANT SPACING
ϕ124±0.1
ϕ74±0.1
ϕ144
30°
45
16±0.05
22±0.05
15±0.2
R1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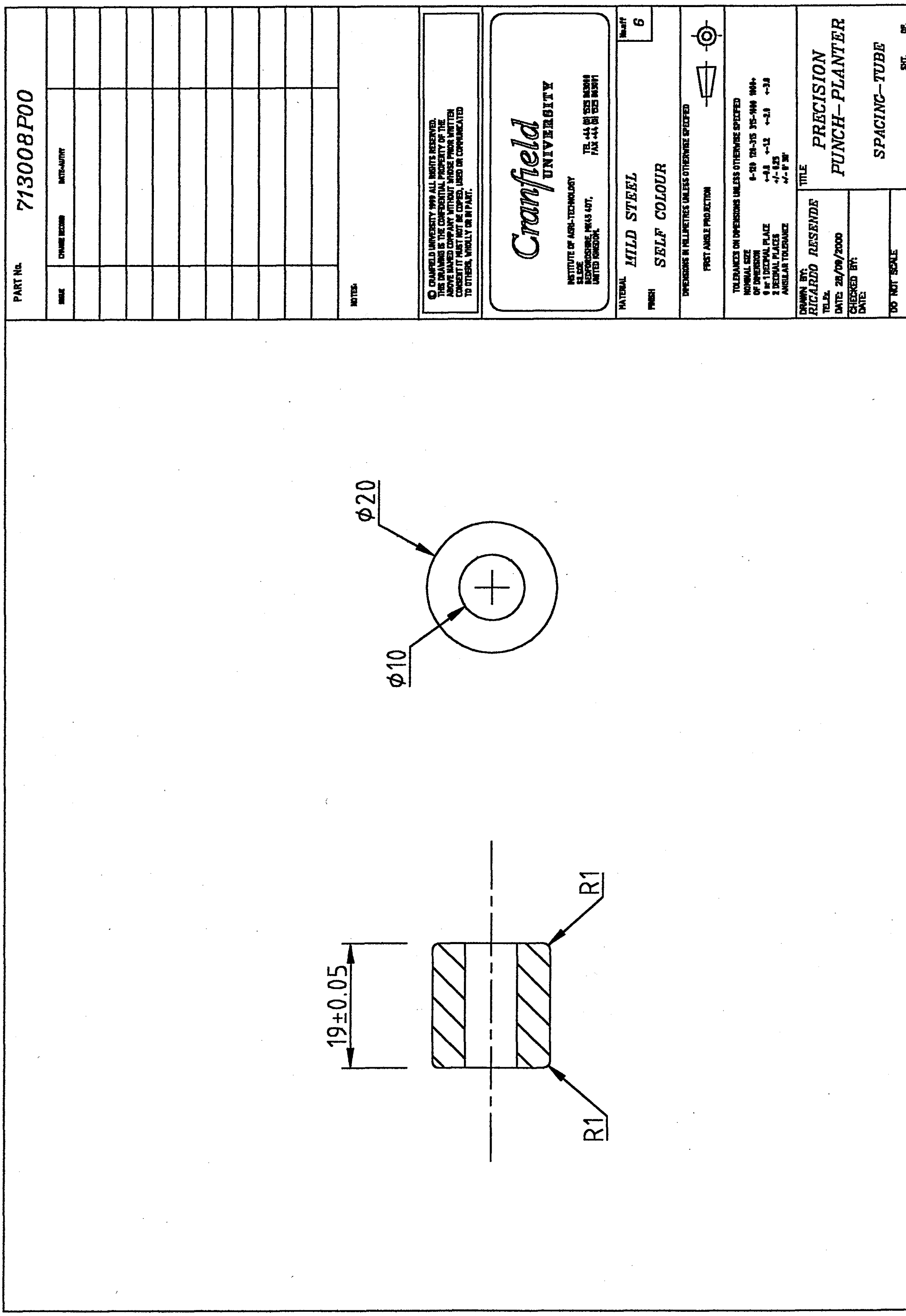
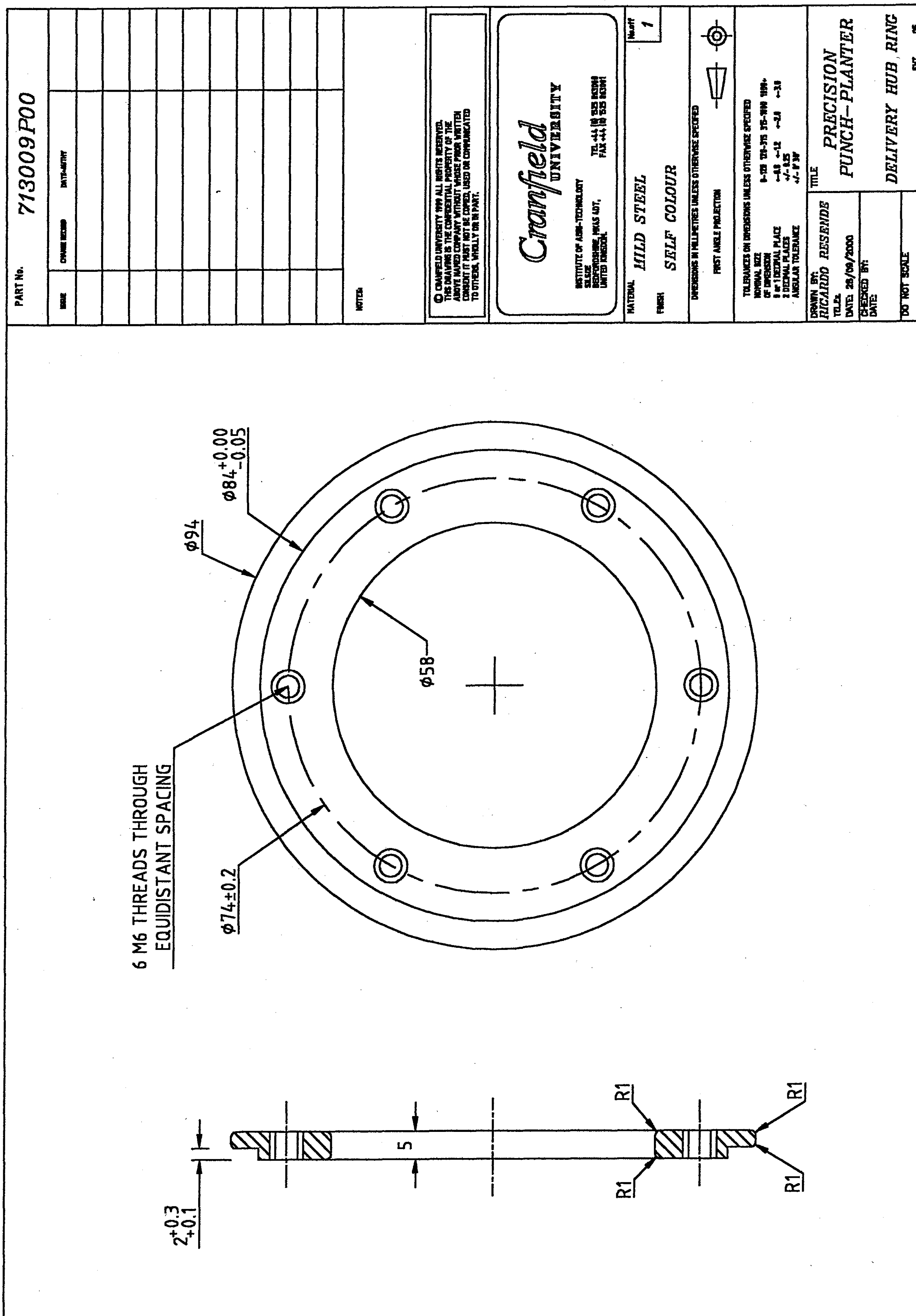
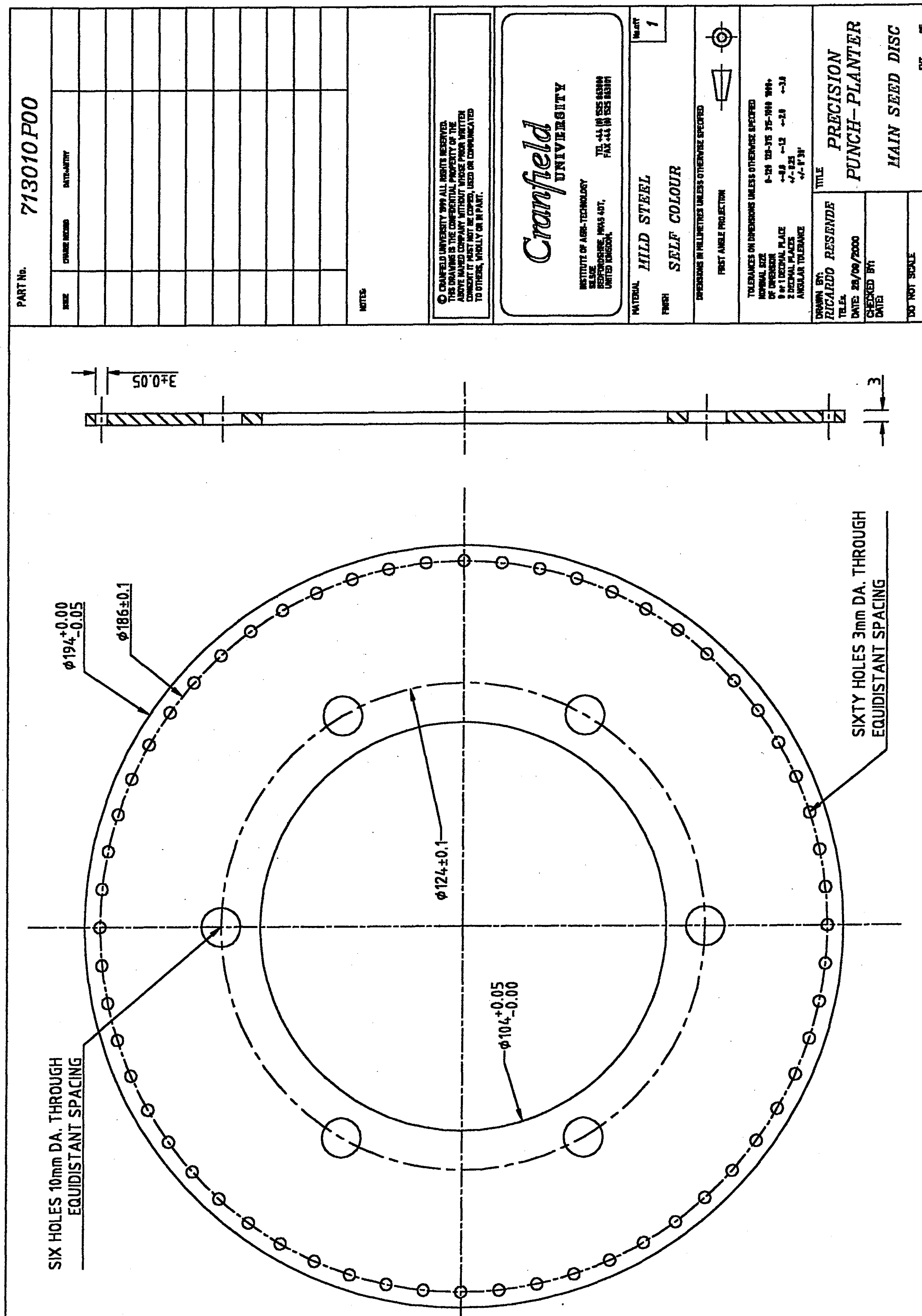
SILSOE
BEDFORDSHIRE, MK45 4DT, UNITED KINGDOM
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION
0 or 1 DECIMAL PLACE
2 DECIMAL PLACES
ANGULAR TOLERANCE
TITLE
PRECISION PUNCH-PLANTER
DELIVERY HUB LID
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE
SHT. OF.
Ø74±0.2
Ø94
Ø56
Ø62-0.04 -0.10
6 HOLES 6.5mm DIA.
EQUIDISTANT SPACING
R1
R1
7.15±0.05
13.15


PART No.
713008P00
NOTES
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
6
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
SPACING-TUBE
φ20
φ10
19±0.05
R1
R1


PART No.
713009P00
NOTES:
Cranfield
UNIVERSITY
MATERIAL
MILD STEEL
FINISH
SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TITLE
PRECISION
PUNCH-PLANTER
DELIVERY HUB RING
DRAWN BY:
RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE
Ø84 +0.00 −0.05
Ø94
Ø58
6 M6 THREADS THROUGH
EQUIDISTANT SPACING
Ø74±0.2
5
R1
R1
R1
R1
2 +0.3 +0.1


PART No. 713010P00
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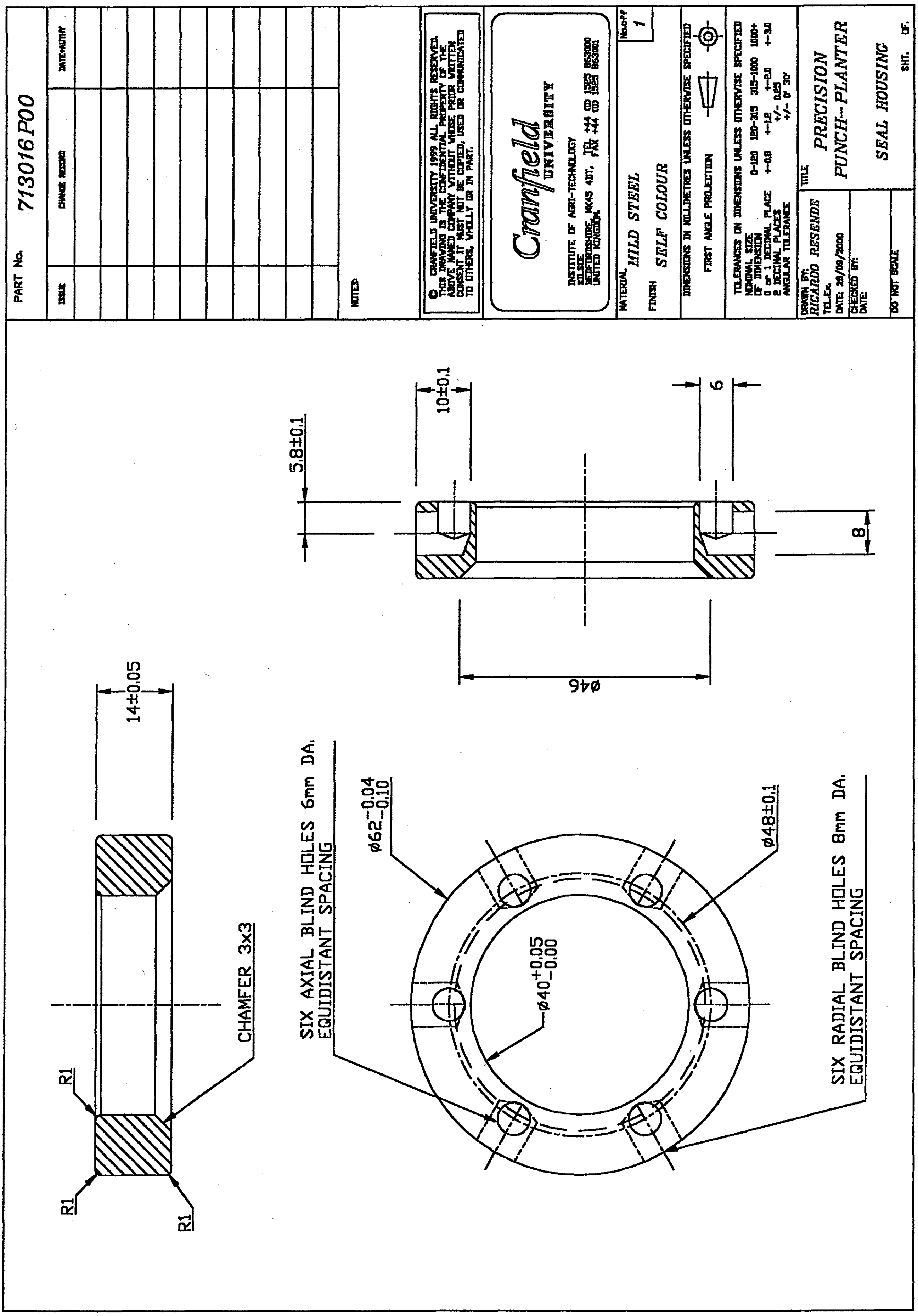
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH–PLANTER
MAIN SEED DISC
3±0.05
3
SIXTY HOLES 3mm DA. THROUGH EQUIDISTANT SPACING
SIX HOLES 10mm DA. THROUGH EQUIDISTANT SPACING
ϕ194+0.00 -0.05
ϕ186±0.1
ϕ124±0.1
ϕ104+0.05 -0.00


PART No. 713016P00
ISSUE
CHANGE RECORD
DATE+AUTH'Y
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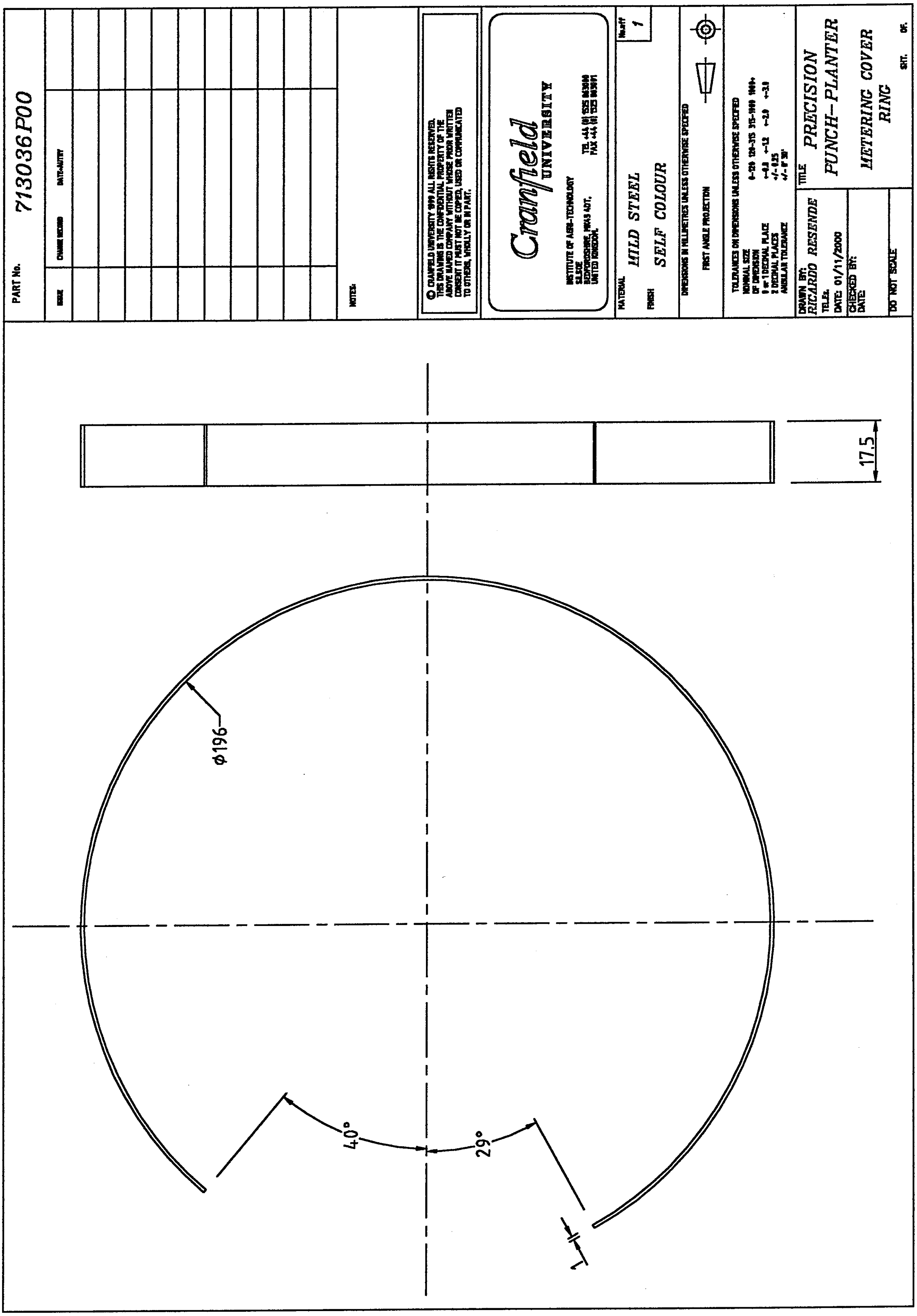
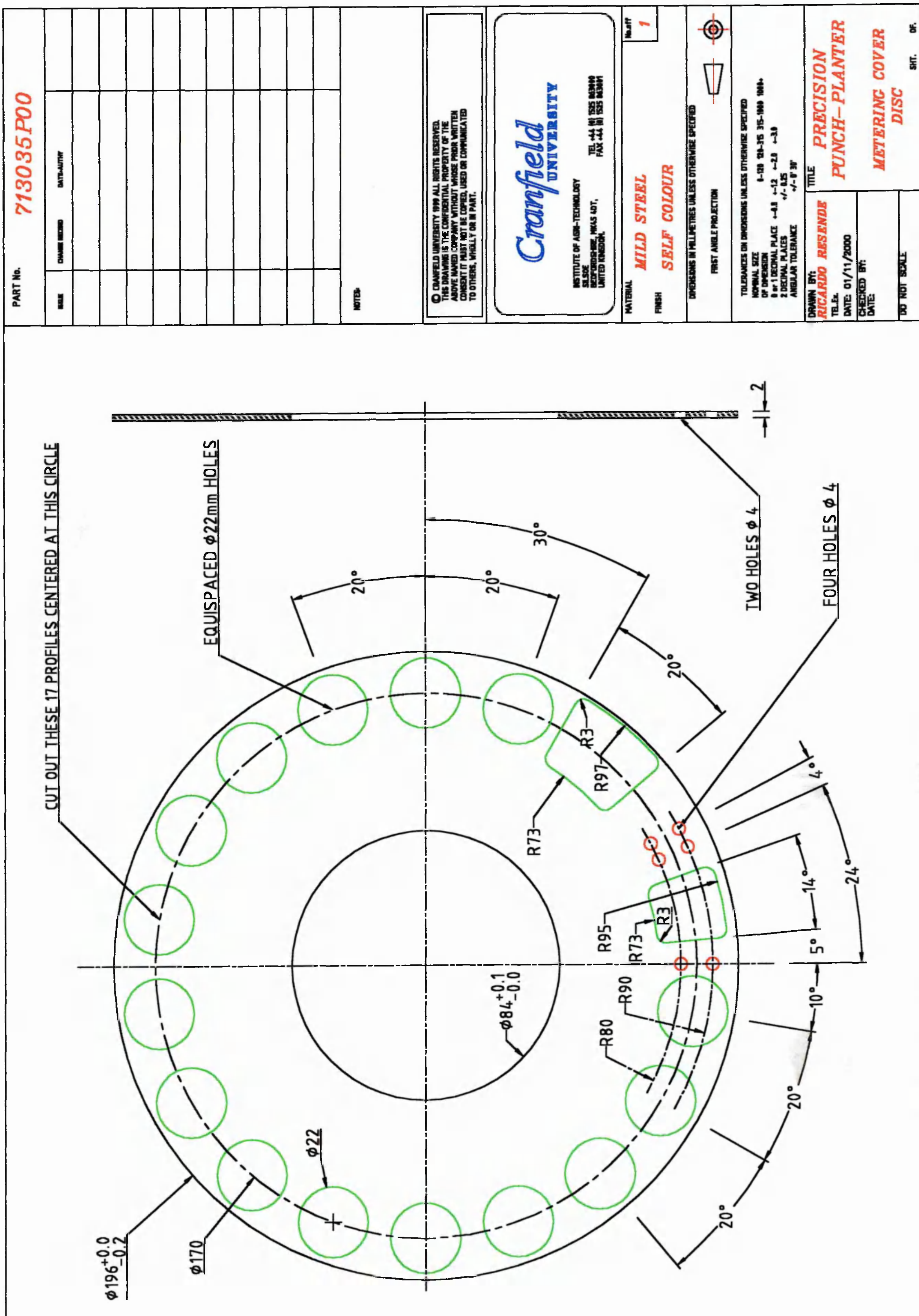
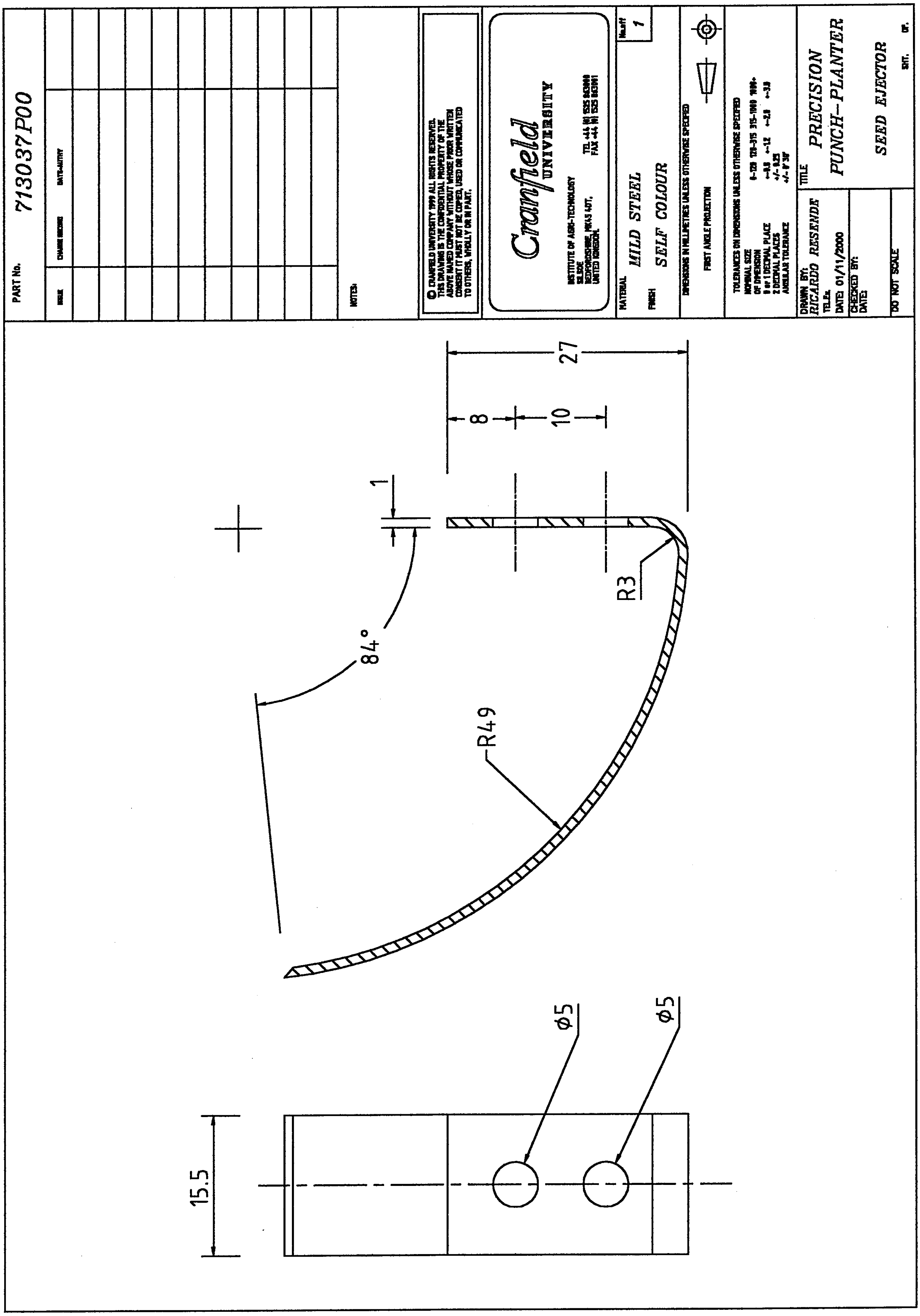
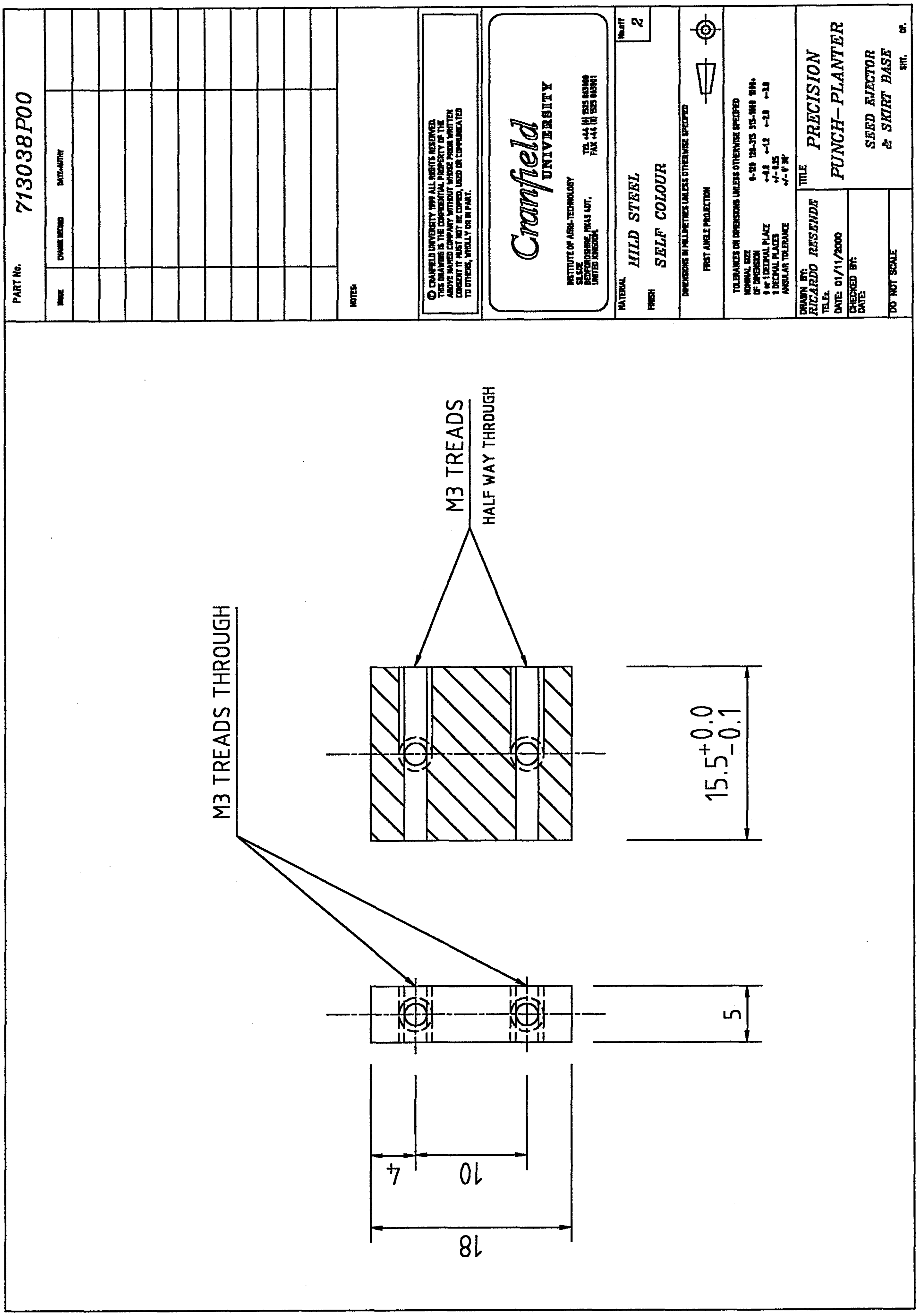
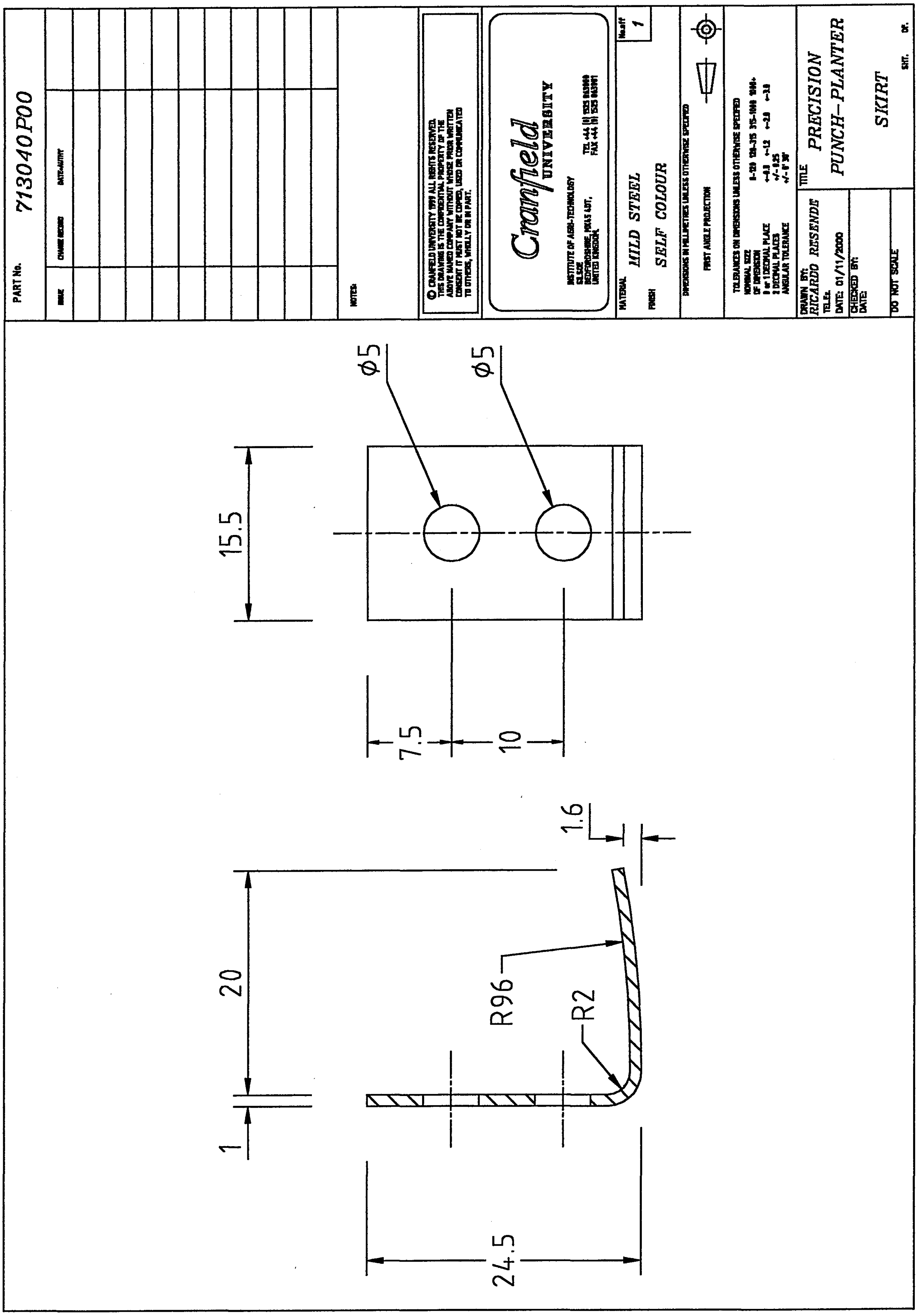
Cranfield UNIVERSITY
INSTITUTE OF AGRI-TECHNOLOGY SILSOE BEDFORDSHIRE, MK45 4DT, UNITED KINGDOM. TEL +44 (0) 1525 863000 FAX +44 (0) 1525 863001
No.OFF 1
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
NOMINAL SIZE OF DIMENSION 0-120 120-315 315-1000 1000+
0 or 1 DECIMAL PLACE +-0.8 +-1.2 +-2.0 +-3.0
2 DECIMAL PLACES +/- 0.25
ANGULAR TOLERANCE +/- 0° 30'
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
TITLE PRECISION PUNCH-PLANTER
SEAL HOUSING
DO NOT SCALE
SHT. OF.
5.8±0.1
10±0.1
6
8
ø46
14±0.05
R1
R1
R1
CHAMFER 3x3
SIX AXIAL BLIND HOLES 6mm DA. EQUIDISTANT SPACING
ø62-0.04 -0.10
ø40+0.05 -0.00
ø48±0.1
SIX RADIAL BLIND HOLES 8mm DA. EQUIDISTANT SPACING

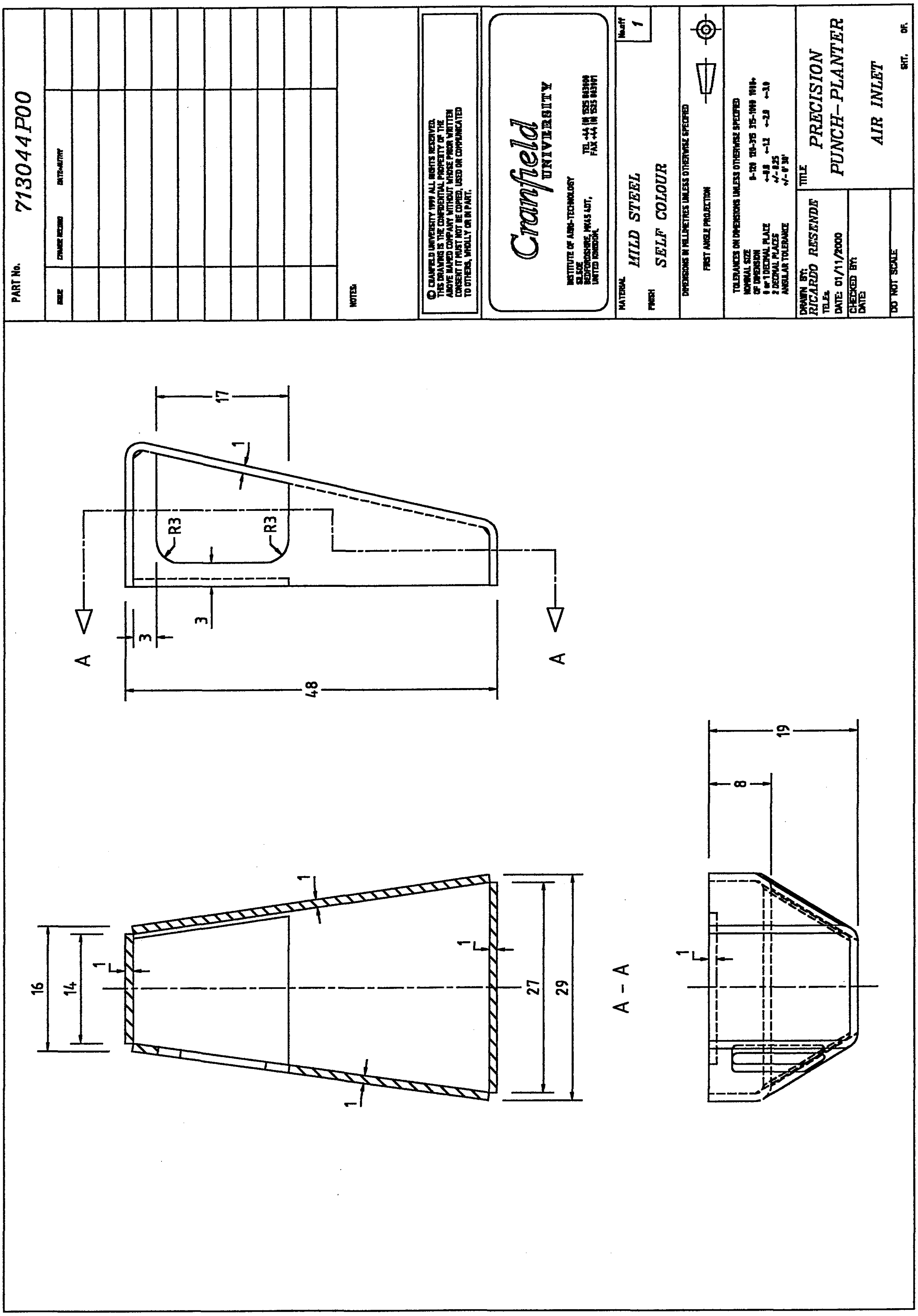

PART No.
713036P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
TITLE PRECISION PUNCH-PLANTER
METERING COVER RING
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DATE:
DO NOT SCALE
No.off 1
17.5
φ196
40°
29°
1


PART No. 713035P00
CUT OUT THESE 17 PROFILES CENTERED AT THIS CIRCLE
EQUISPACED Φ22mm HOLES
TWO HOLES Φ 4
FOUR HOLES Φ 4
Φ196 +0.0 −0.2
Φ170
Φ22
Φ84 +0.1 −0.0
R73
R97
R3
R95
R90
R80
30°
20°
14°
24°
4°
5°
10°
2
Cranfield UNIVERSITY
INSTITUTE OF AGRI-TECHNOLOGY
SILSOE
BEDFORDSHIRE, MK45 4DT,
UNITED KINGDOM.
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
METERING COVER DISC


PART No. 713037P00
NOTES:
Cranfield UNIVERSITY
INSTITUTE OF AGRI-TECHNOLOGY
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE PRECISION PUNCH–PLANTER
SEED EJECTOR
27
8
10
1
R3
84°
R49
ϕ5
ϕ5
15.5


PART No. 713038P00
M3 TREADS THROUGH
M3 TREADS
HALF WAY THROUGH
15.5+0.0 -0.1
5
4
10
18
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
TITLE PRECISION PUNCH-PLANTER
SEED EJECTOR & SKIRT BASE
DO NOT SCALE


PART No.
713040P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
No.off 1
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
SKIRT
ϕ5
ϕ5
15.5
7.5
10
1.6
20
R96
R2
1
24.5


PART No.
713044P00
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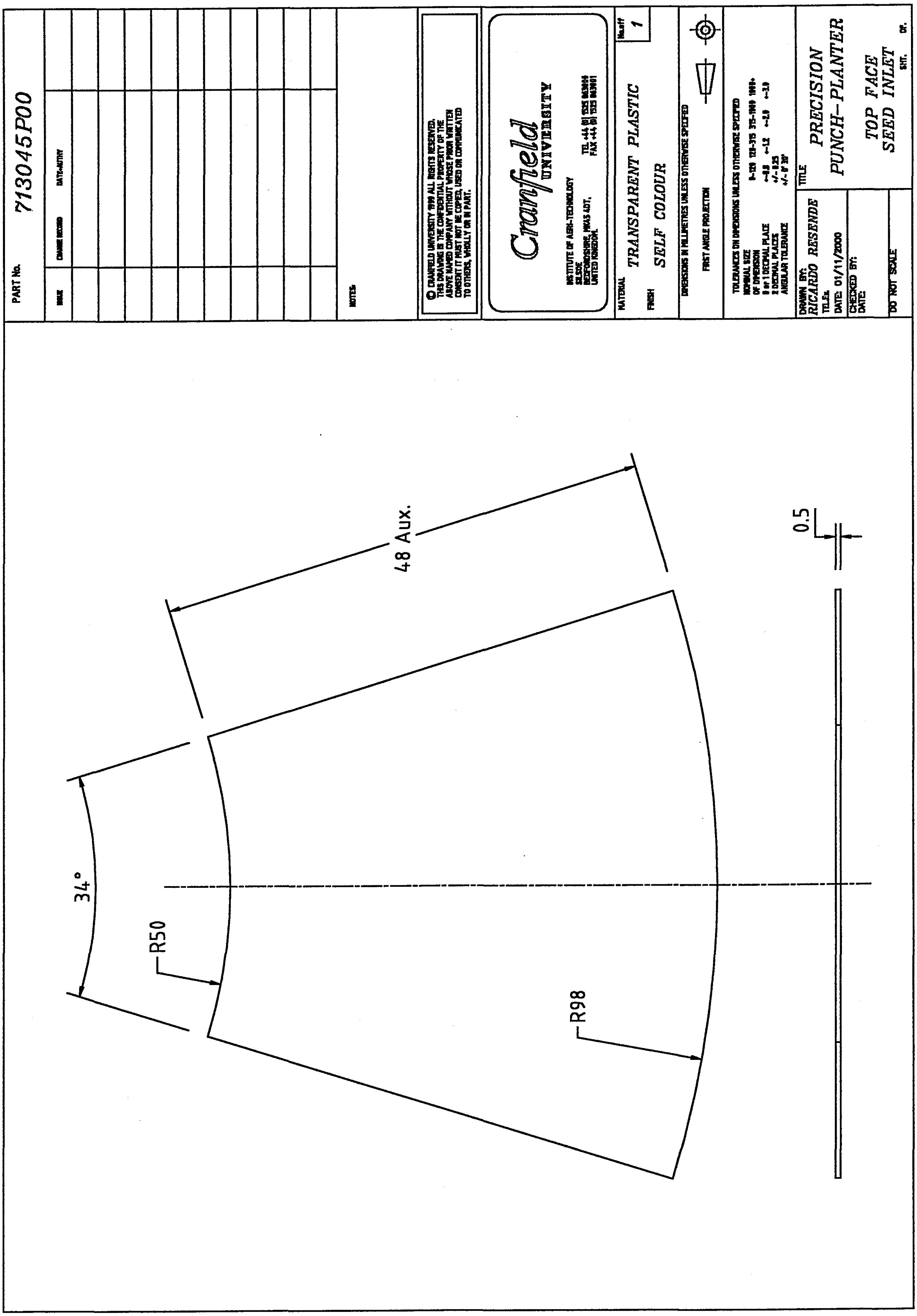
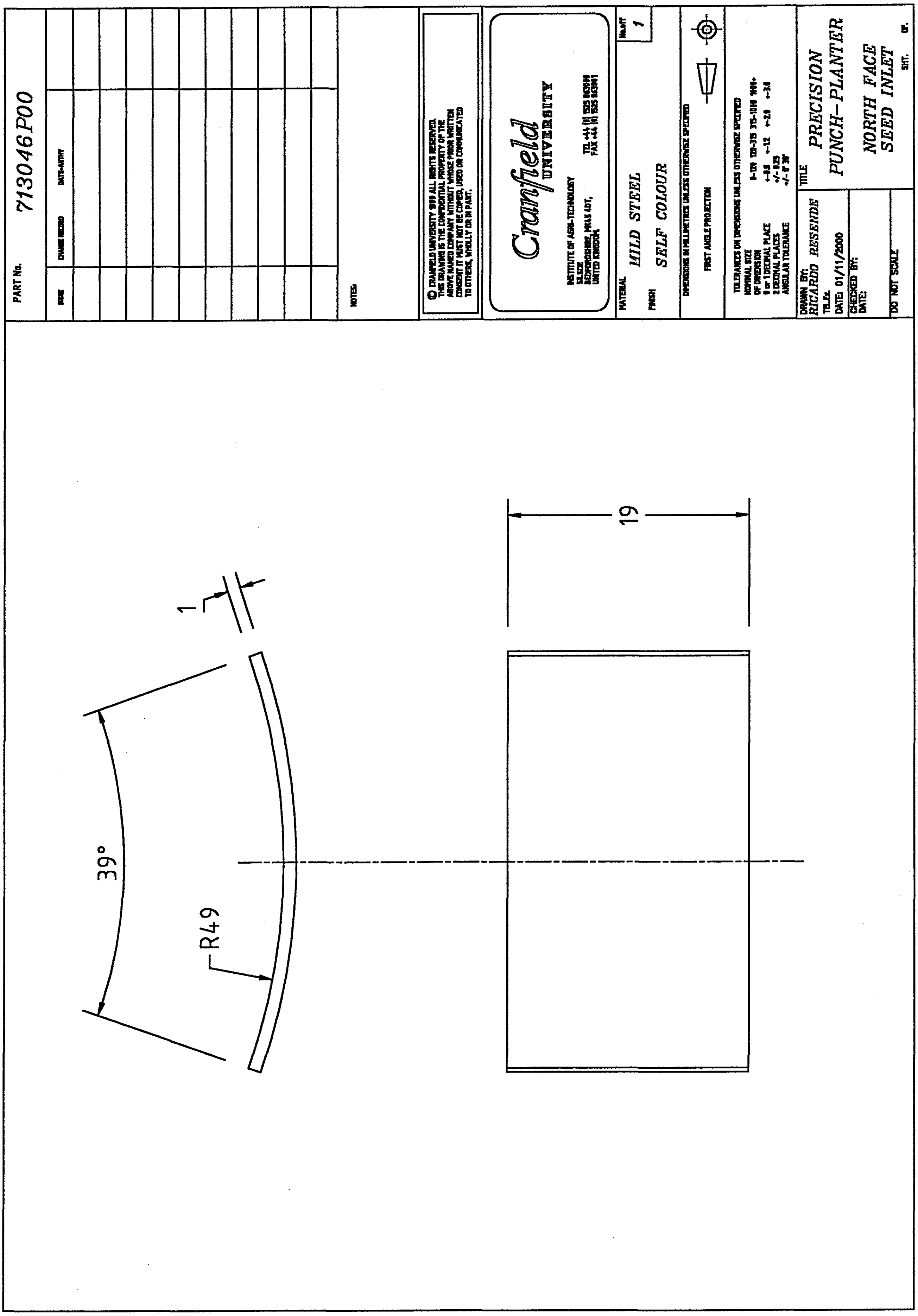
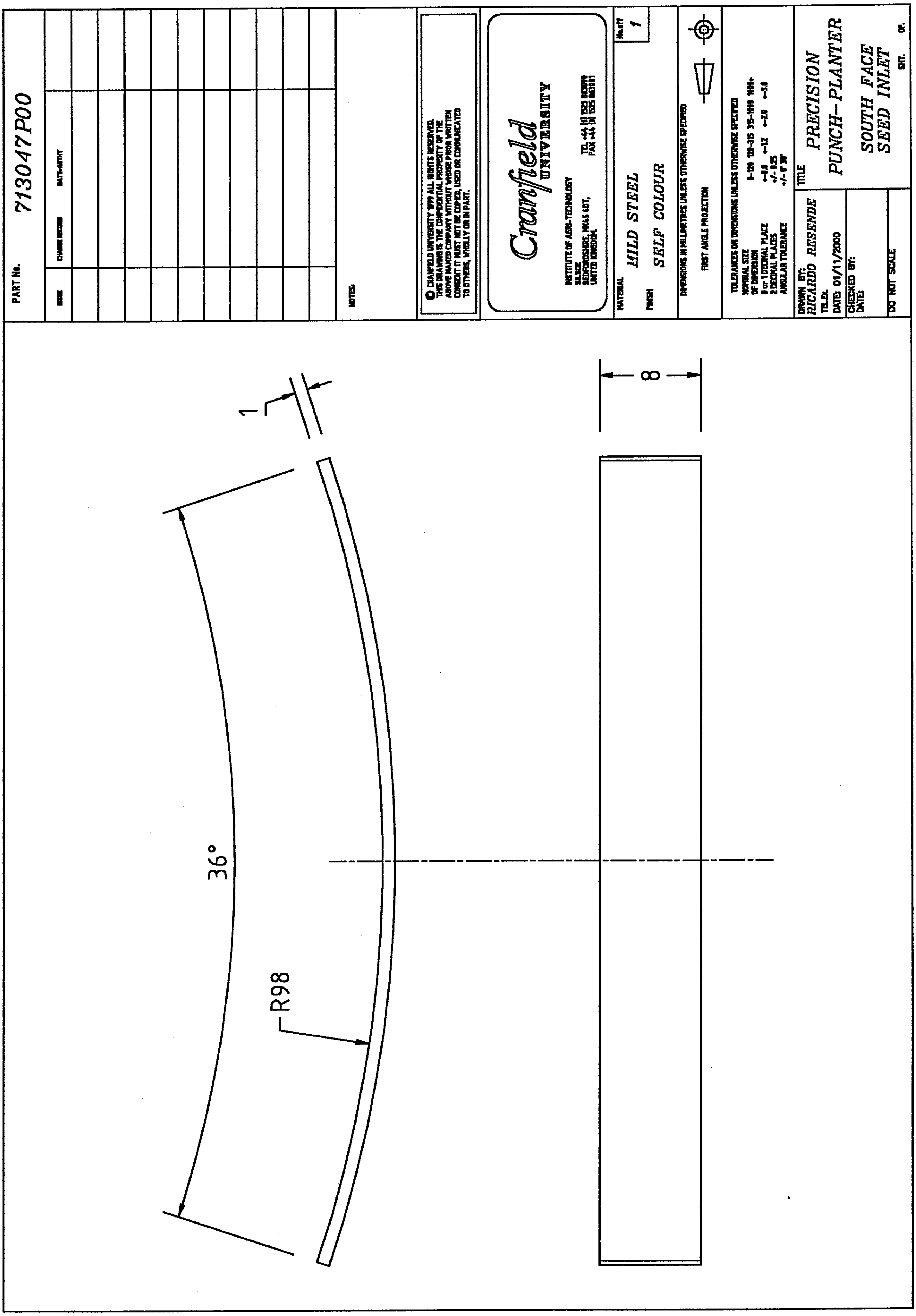
INSTITUTE OF AGRO-TECHNOLOGY
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
TITLE PRECISION PUNCH-PLANTER
AIR INLET
DO NOT SCALE
SHT. OF.
17
1
R3
R3
3
3
48
A
A
16
14
1
1
27
29
A - A
19
8
1


PART No.
713045P00
Cranfield UNIVERSITY
MATERIAL
TRANSPARENT PLASTIC
FINISH
SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY:
RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION
PUNCH-PLANTER
TOP FACE
SEED INLET
48 Aux.
0.5
34°
R50
R98



PART No. 713046P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
No. off 1
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
NORTH FACE SEED INLET
19
1
39°
R49


PART No.
713047P00
NOTES:
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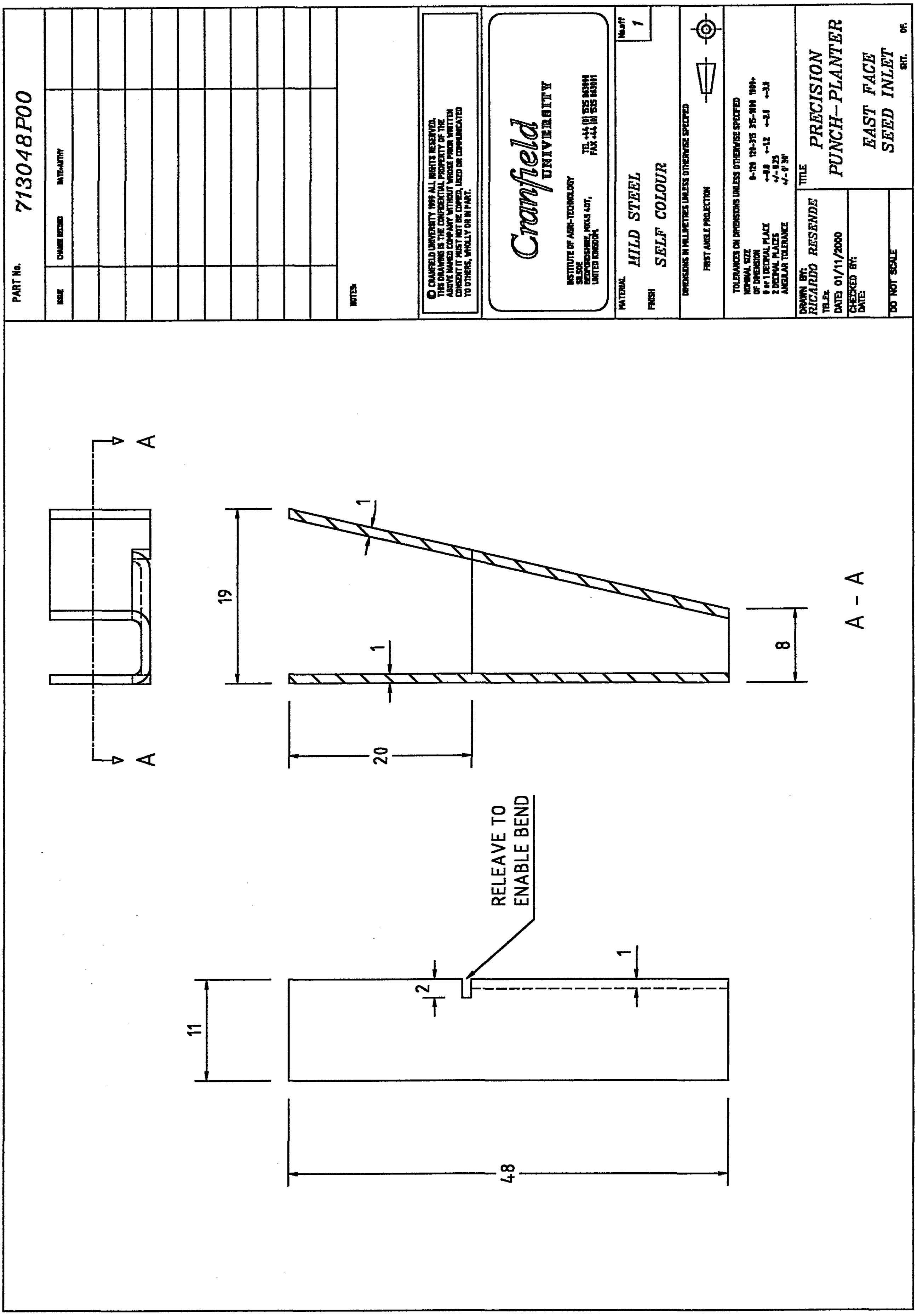
MATERIAL
MILD STEEL
FINISH
SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
SOUTH FACE SEED INLET
1
8
36°
R98


PART No.
713048P00
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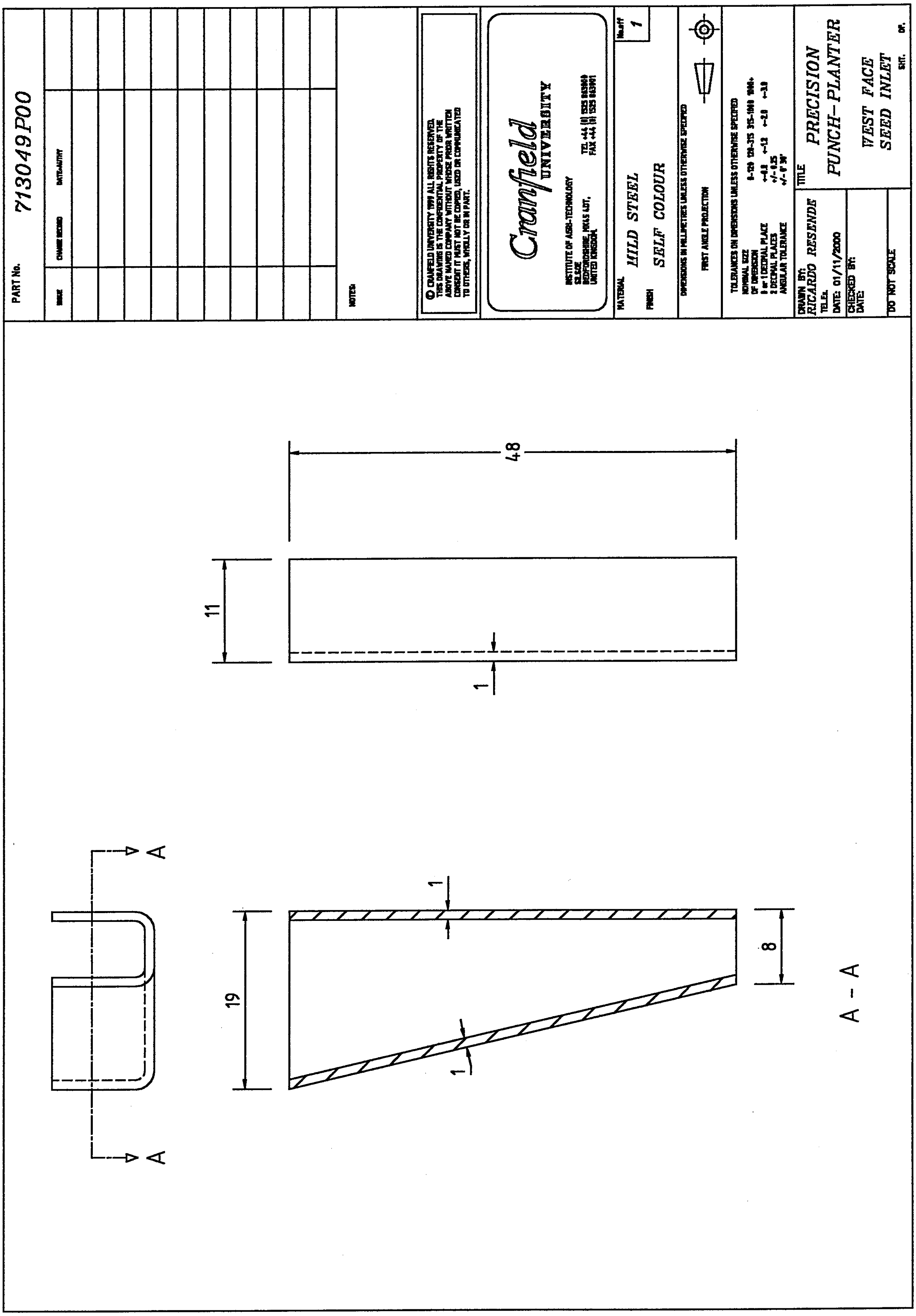
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
EAST FACE SEED INLET
A
A
A - A
19
1
1
20
8
RELEAVE TO ENABLE BEND
2
1
11
48


PART No. 713049P00
Cranfield UNIVERSITY
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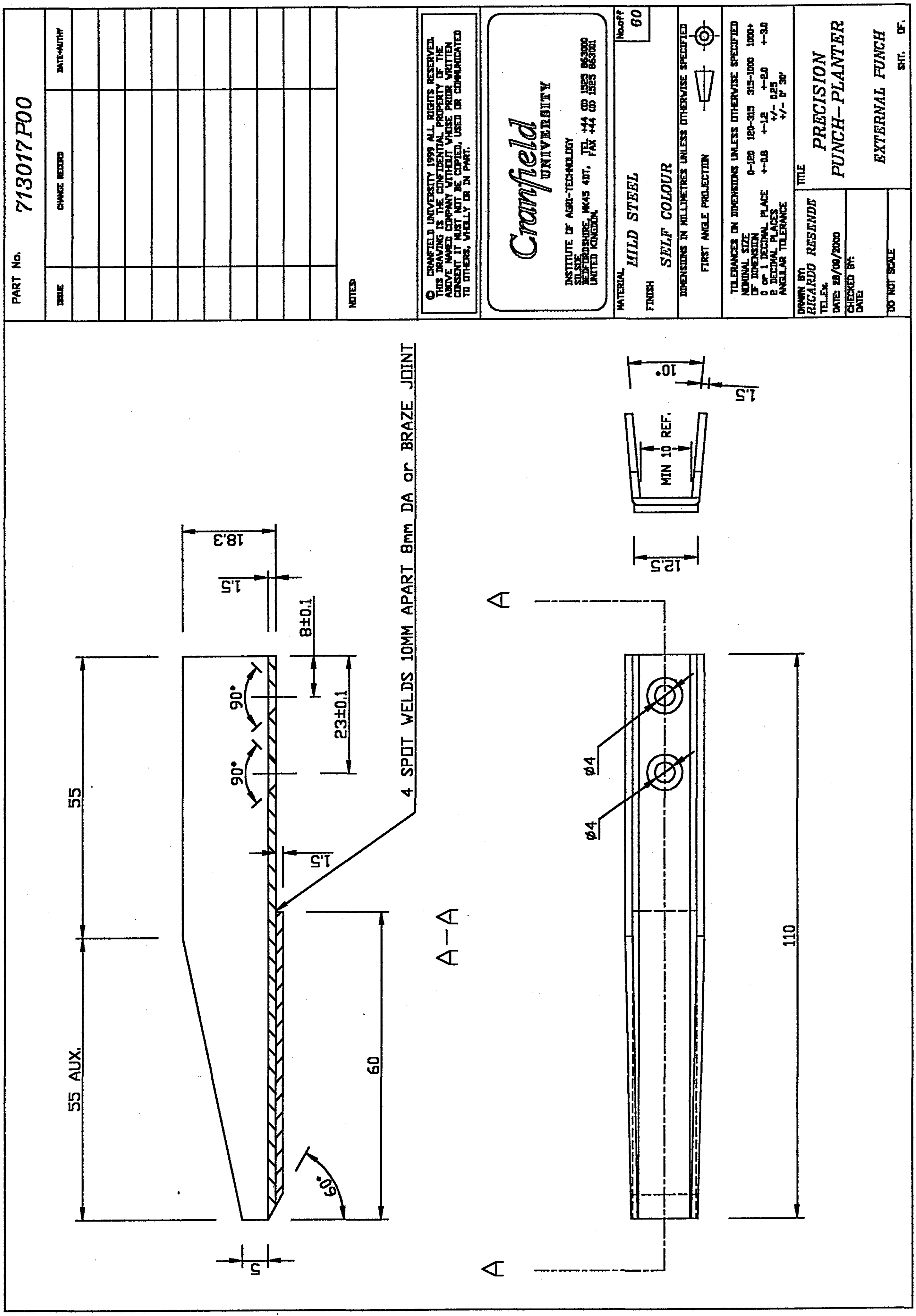
MATERIAL MILD STEEL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 01/11/2000
TITLE PRECISION PUNCH-PLANTER
WEST FACE SEED INLET
DO NOT SCALE
48
11
1
19
8
A - A



PART No. 713017P00
CHANGE RECORD
NOTES:
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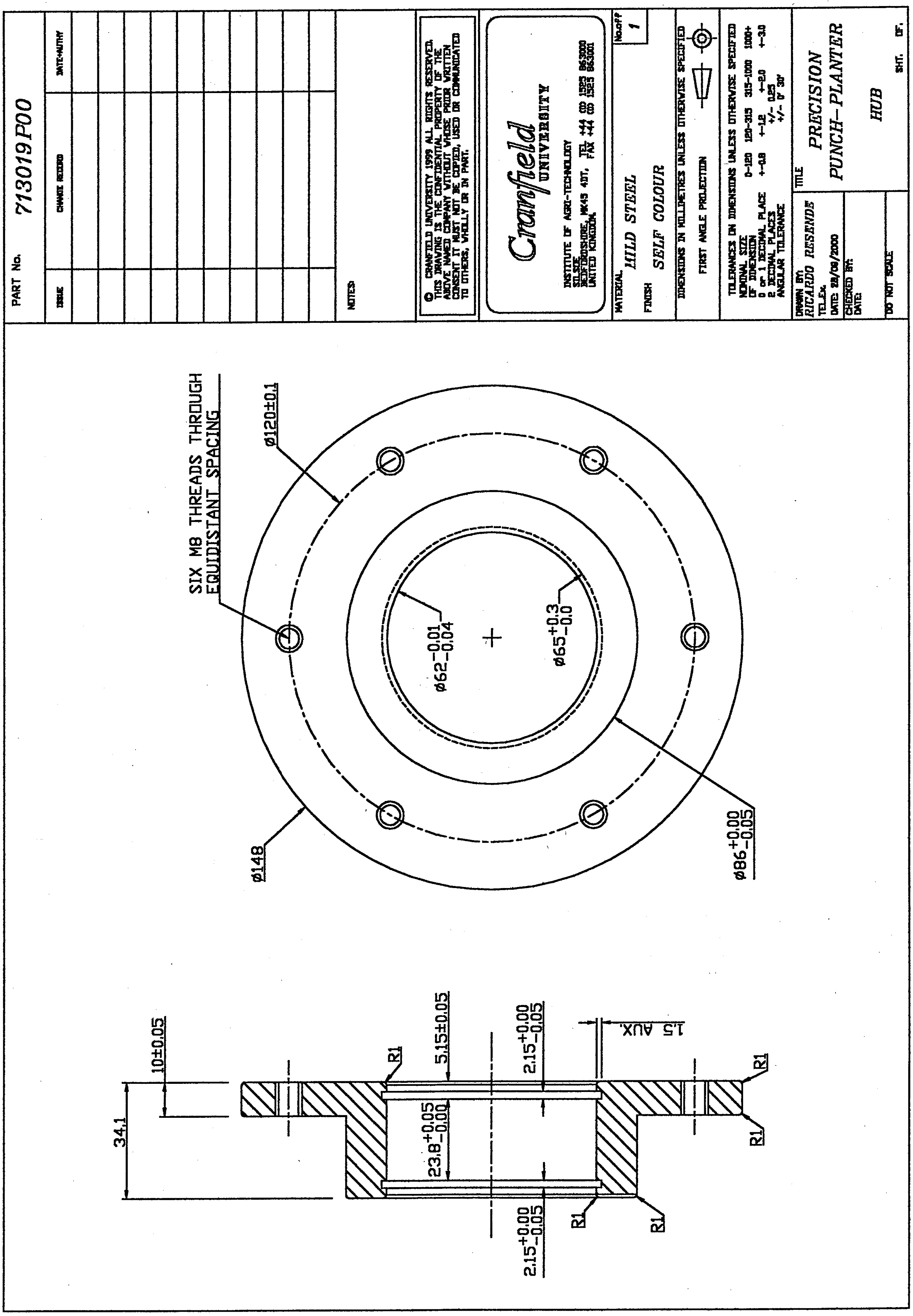
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 60
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
EXTERNAL PUNCH
4 SPOT WELDS 10MM APART 8mm DA or BRAZE JOINT
A–A
MIN 10 REF.
55 AUX.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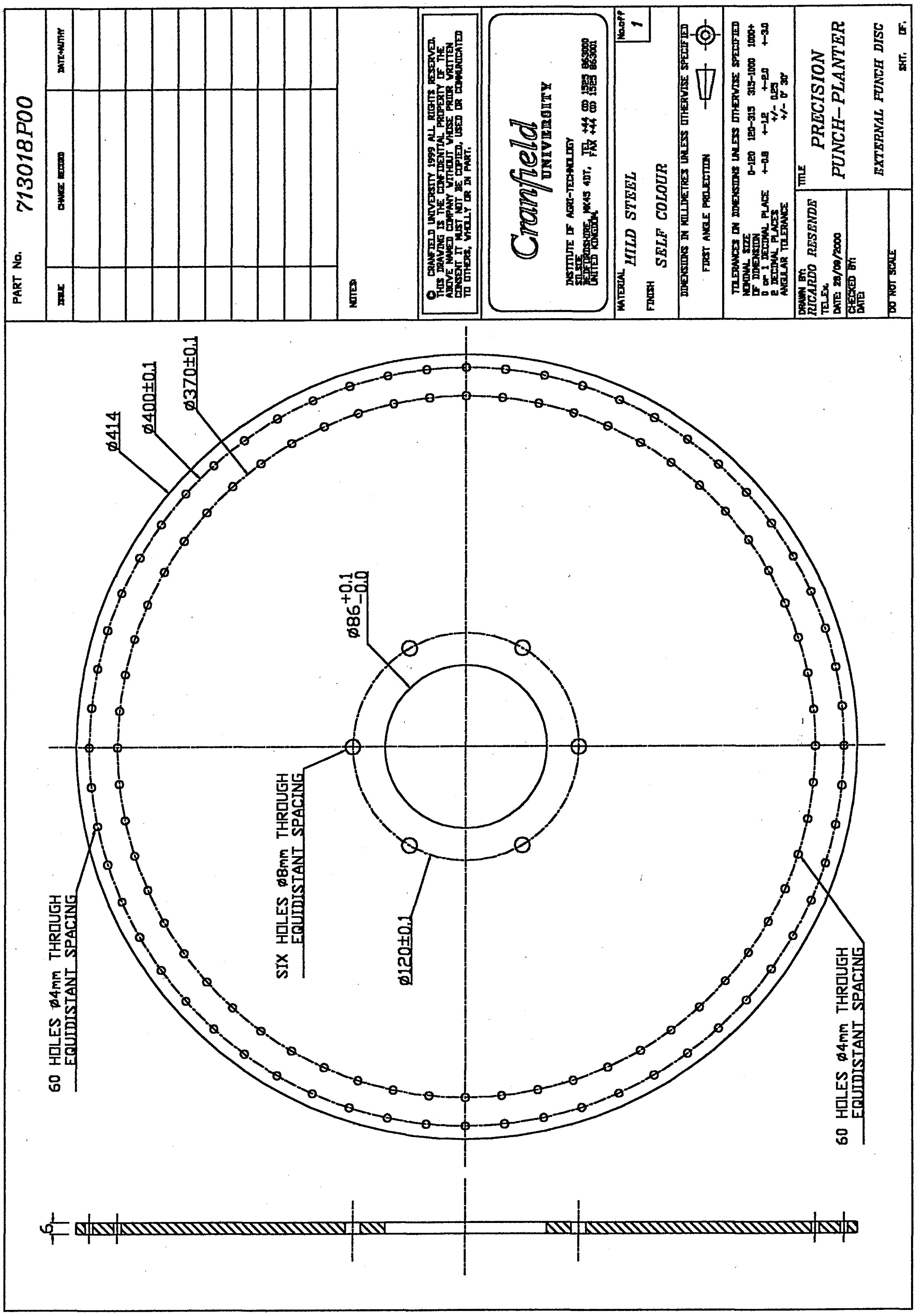
BEDFORDSHIRE, MK45 4DT.
UNITED KINGDOM.
No.off 1
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
HUB
SIX M8 THREADS THROUGH EQUIDISTANT SPACING
ø120±0.1
ø148
ø62 -0.01 -0.04
ø65 +0.3 -0.0
ø86 +0.00 -0.05
10±0.05
34.1
R1
5.15±0.05
23.8 +0.05 -0.00
2.15 +0.00 -0.05
1.5 AUX.


PART No. 713018P00
ISSUE
CHANGE RECORD
DATE+AUTHY
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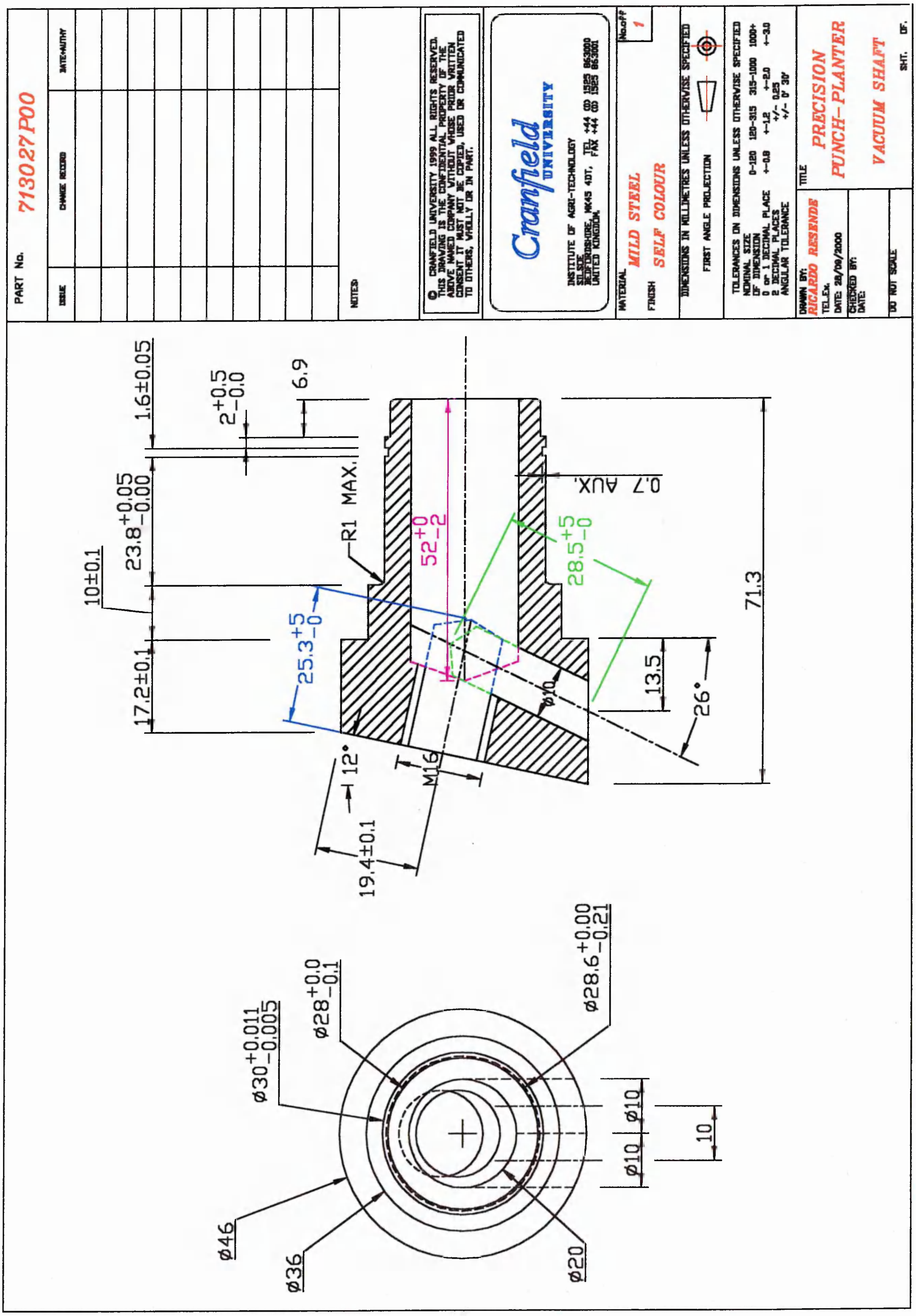
No.off 1
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
EXTERNAL PUNCH DISC
Ø414
Ø400±0.1
Ø370±0.1
Ø86 +0.1 -0.0
SIX HOLES Ø8mm THROUGH EQUIDISTANT SPACING
Ø120±0.1
60 HOLES Ø4mm THROUGH EQUIDISTANT SPACING
60 HOLES Ø4mm THROUGH EQUIDISTANT SPACING
6


PART No. 713027P00
ISSUE
CHANGE RECORD
DATE+AUTHY
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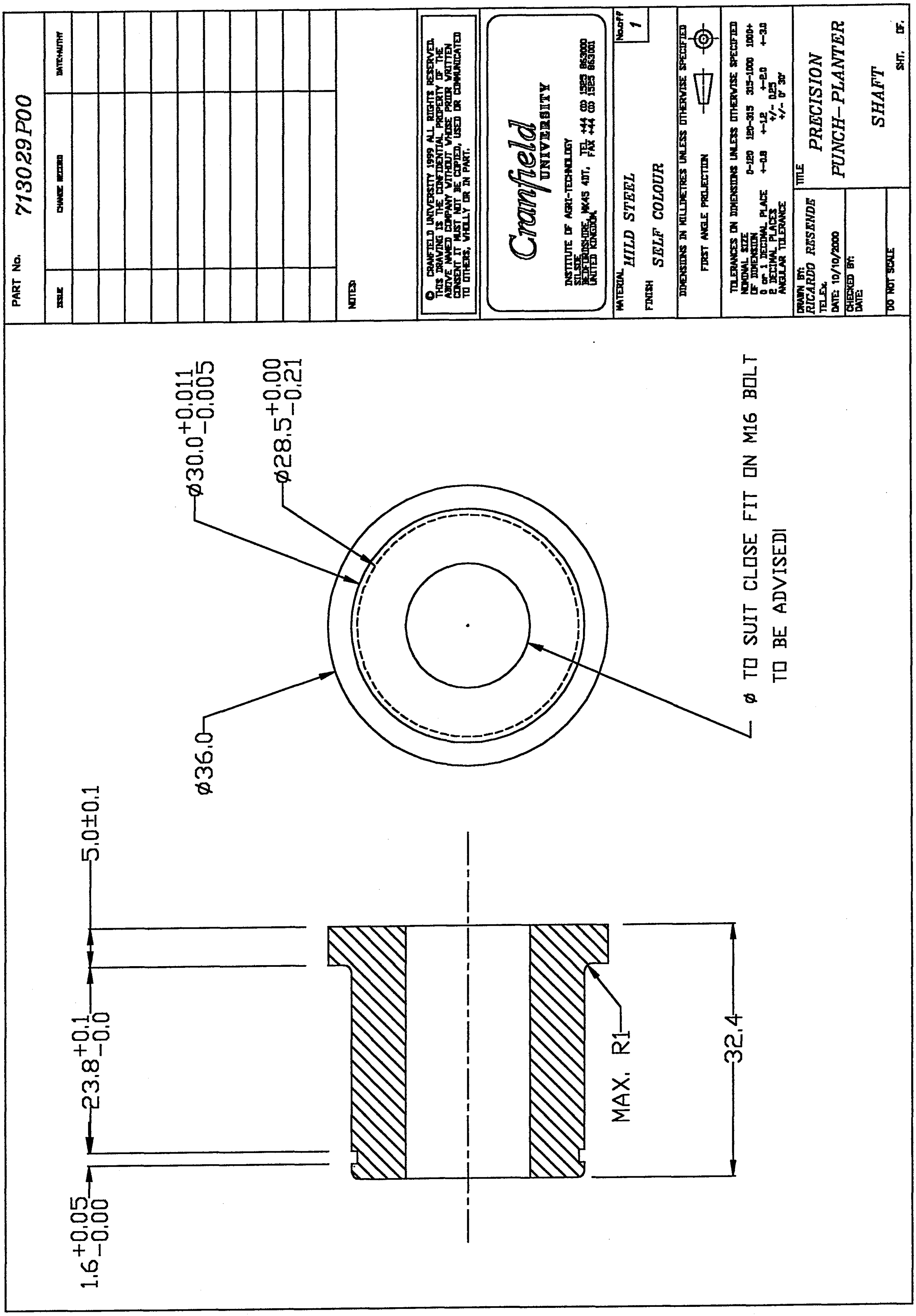
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
No.off 1
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
VACUUM SHAFT
1.6±0.05
23.8+0.05 −0.00
10±0.1
17.2±0.1
R1 MAX.
52+0 −2
28.5+5 −0
25.3+5 −0
0.7 AUX.
71.3
13.5
26°
12°
M16
19.4±0.1
ø10
ø30+0.011 −0.005
ø28+0.0 −0.1
ø28.6+0.00 −0.21
ø46
ø36
ø20
10


PART No.
713029P00
NOTES:
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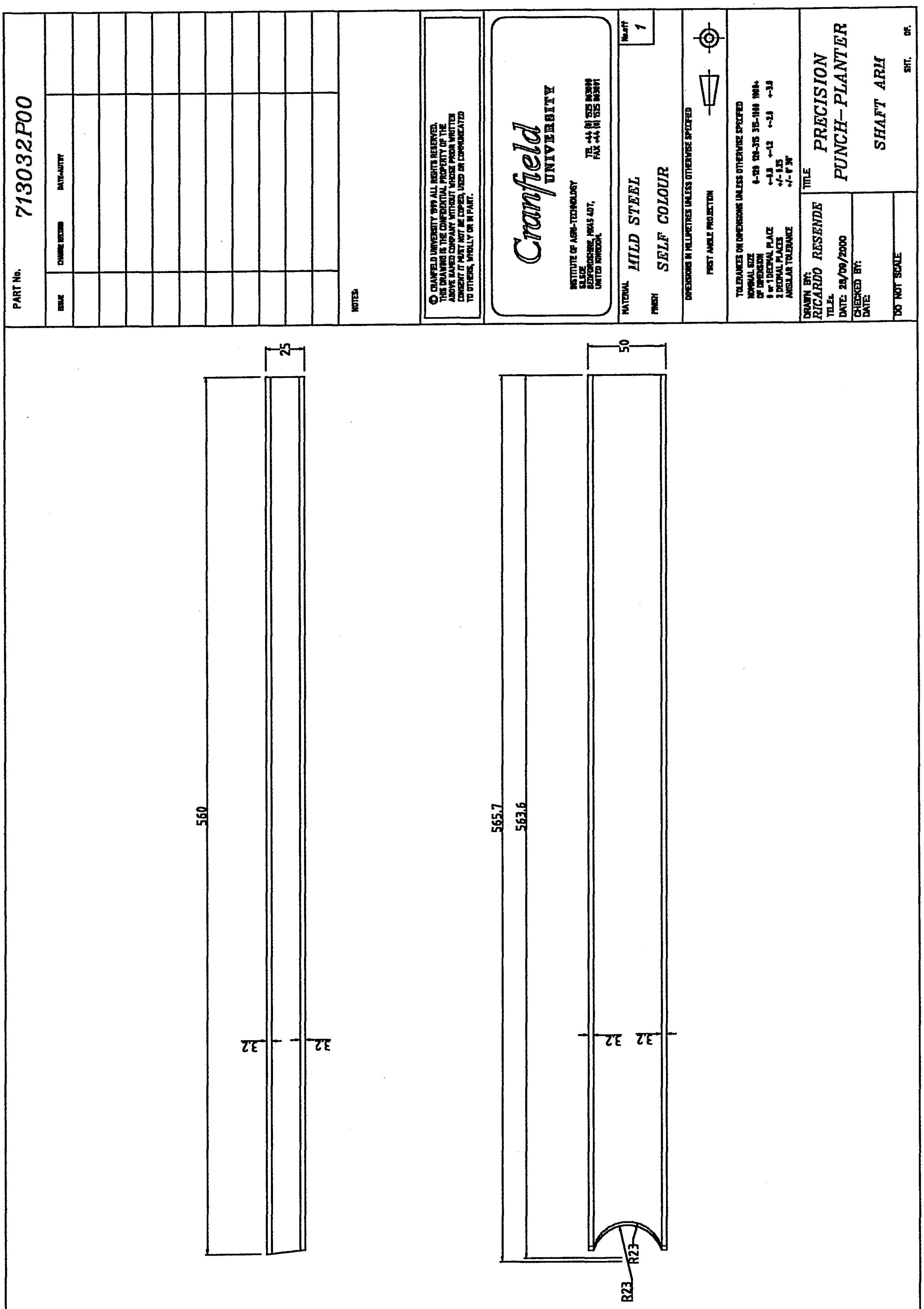
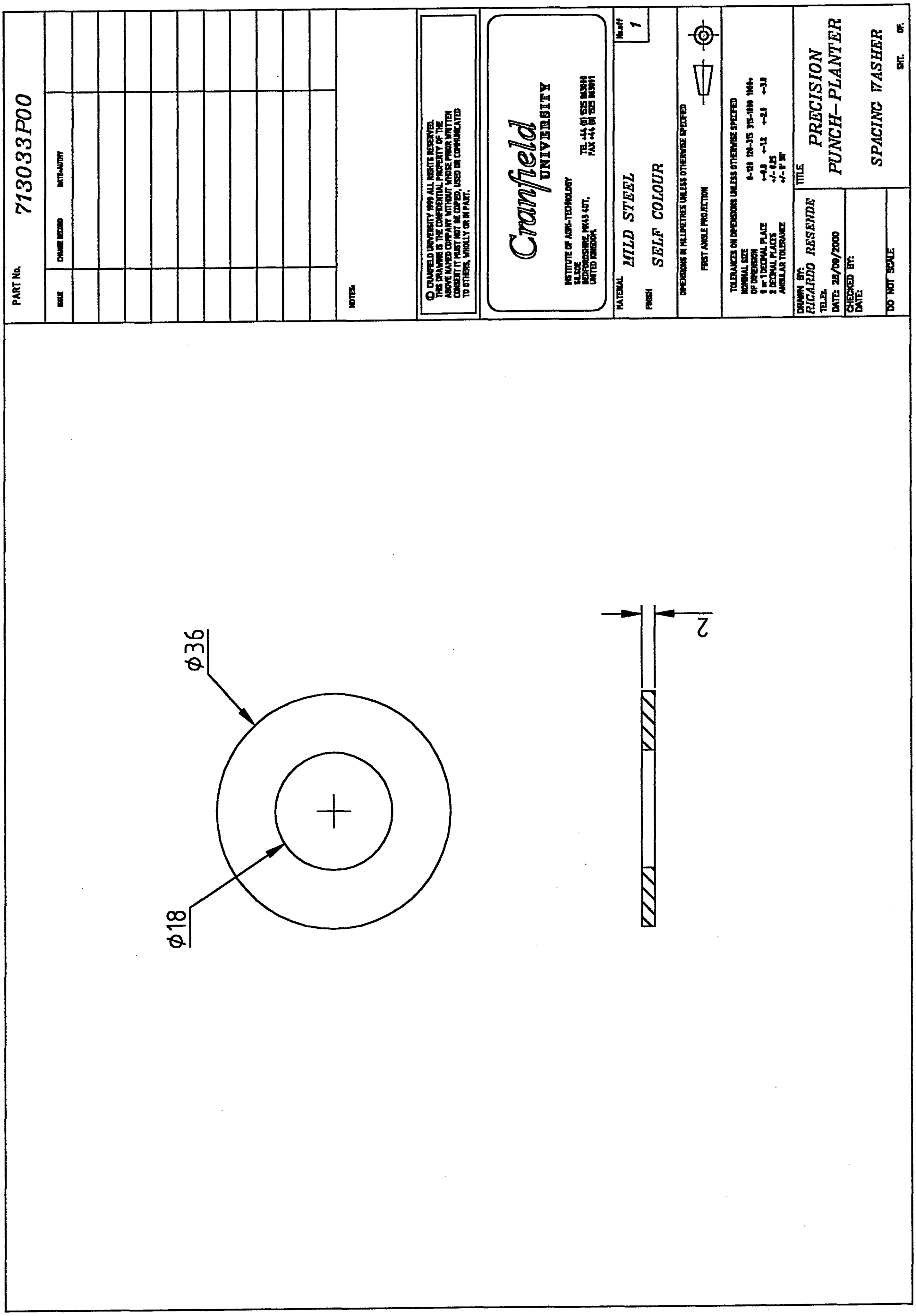
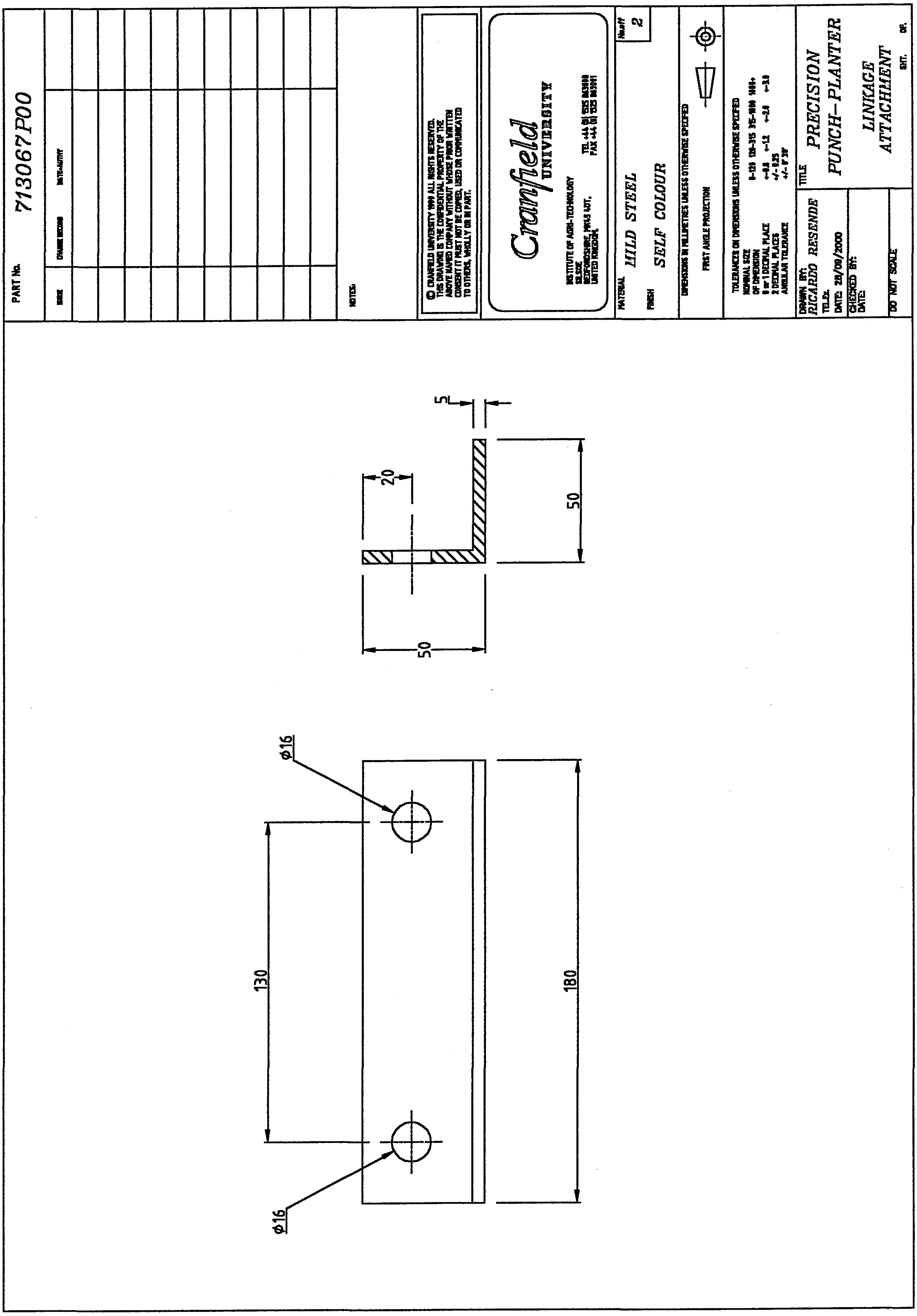
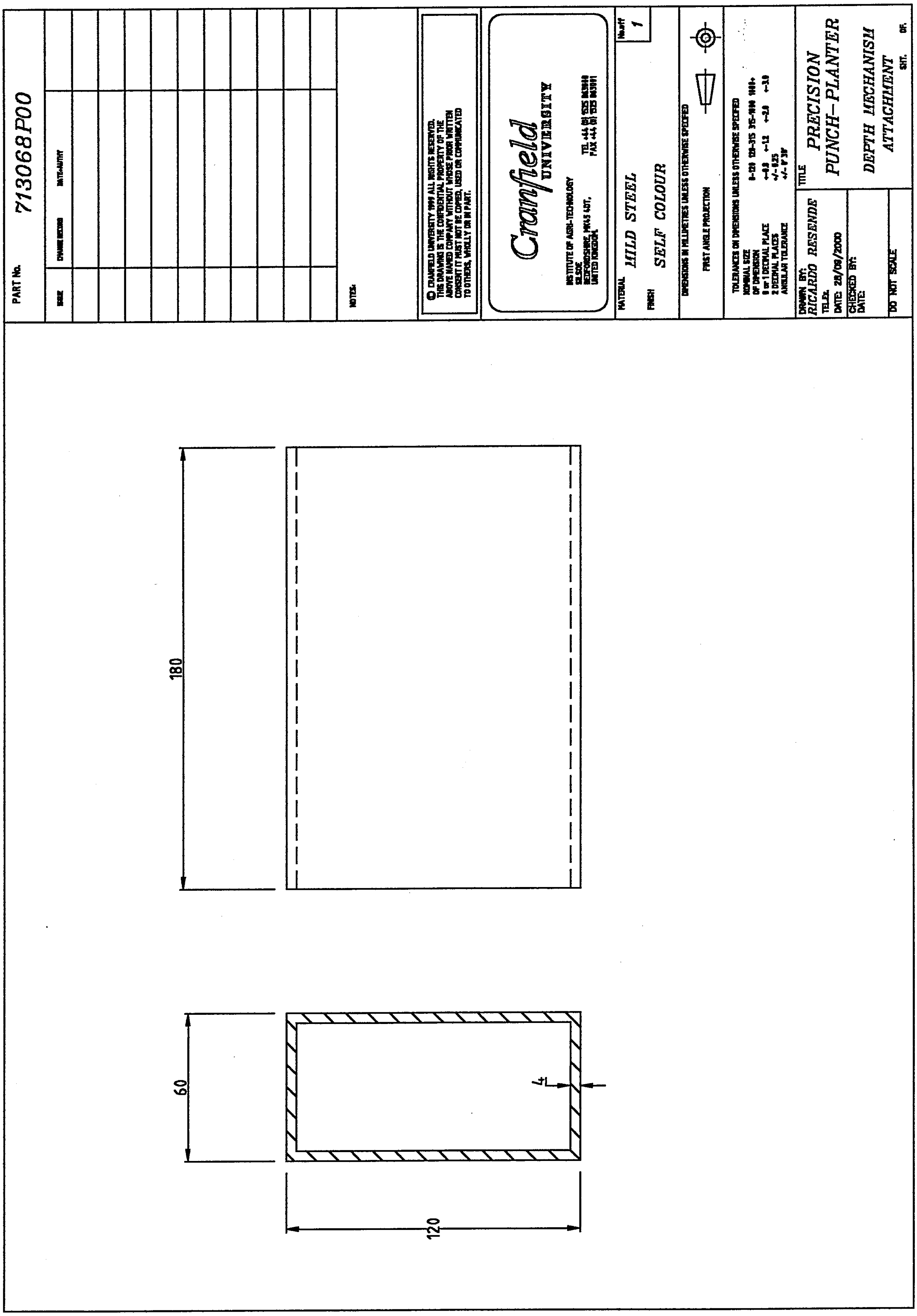
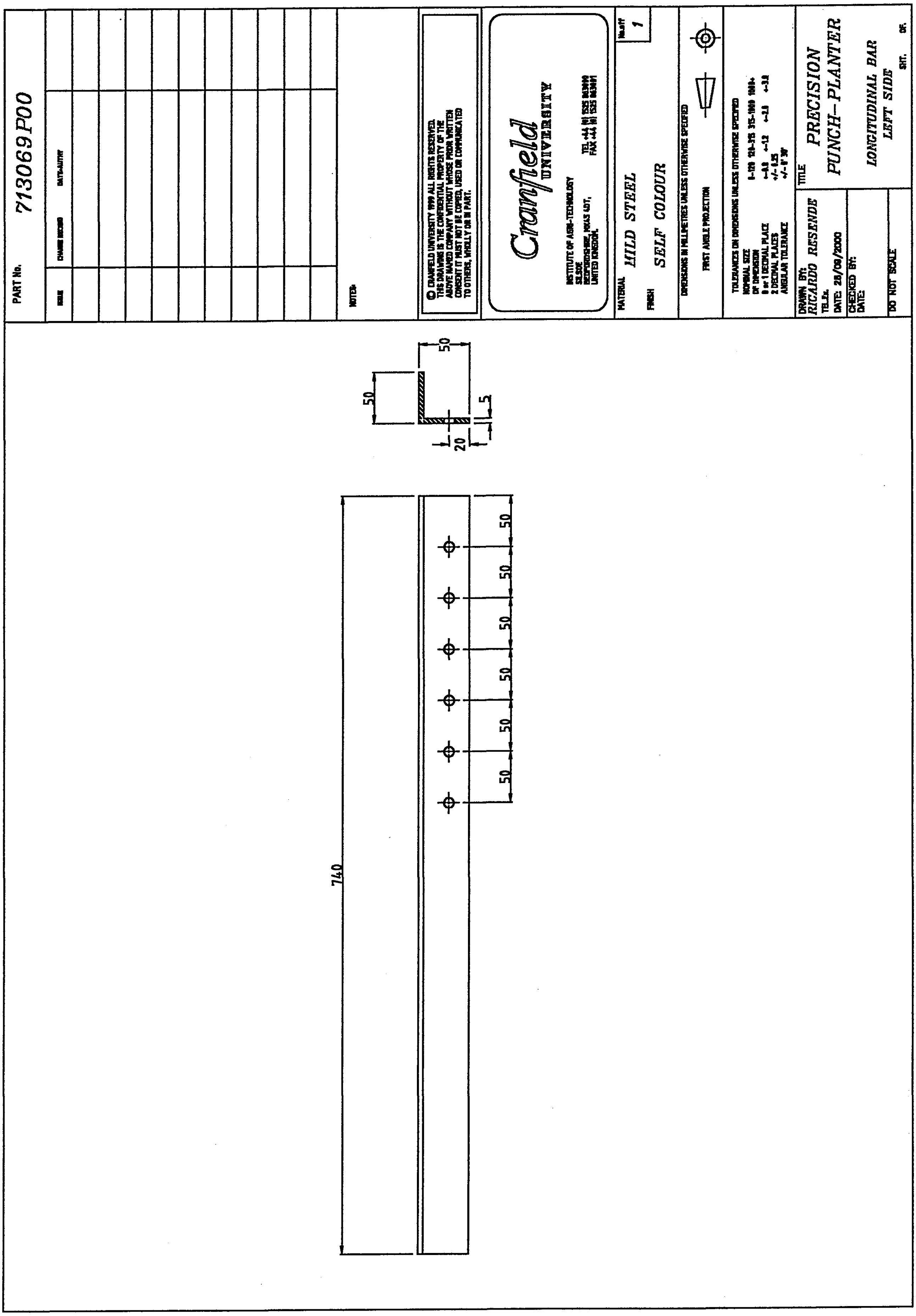
MATERIAL MILD STEEL
FINISH SELF COLOUR
No. off 1
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 10/10/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
SHAFT
Ø30.0 +0.011 −0.005
Ø28.5 +0.00 −0.21
Ø36.0
Ø TO SUIT CLOSE FIT ON M16 BOLT
TO BE ADVISED!
5.0±0.1
23.8 +0.1 −0.0
1.6 +0.05 −0.00
MAX. R1
32.4


PART No.
713032P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
No. off 1
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
TITLE
PRECISION PUNCH-PLANTER
SHAFT ARM
25
560
3.2
50
565.7
563.6
R23


PART No. 713033P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
TITLE PRECISION PUNCH-PLANTER
SPACING WASHER
DO NOT SCALE
No. off 1
Φ36
Φ18
2


PART No.
713067P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 2
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
LINKAGE ATTACHMENT
5
20
50
50
ø16
130
180
ø16


PART No. 713068P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 1
FIRST ANGLE PROJECTION
TITLE PRECISION PUNCH-PLANTER
DEPTH MECHANISM ATTACHMENT
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
180
60
4
120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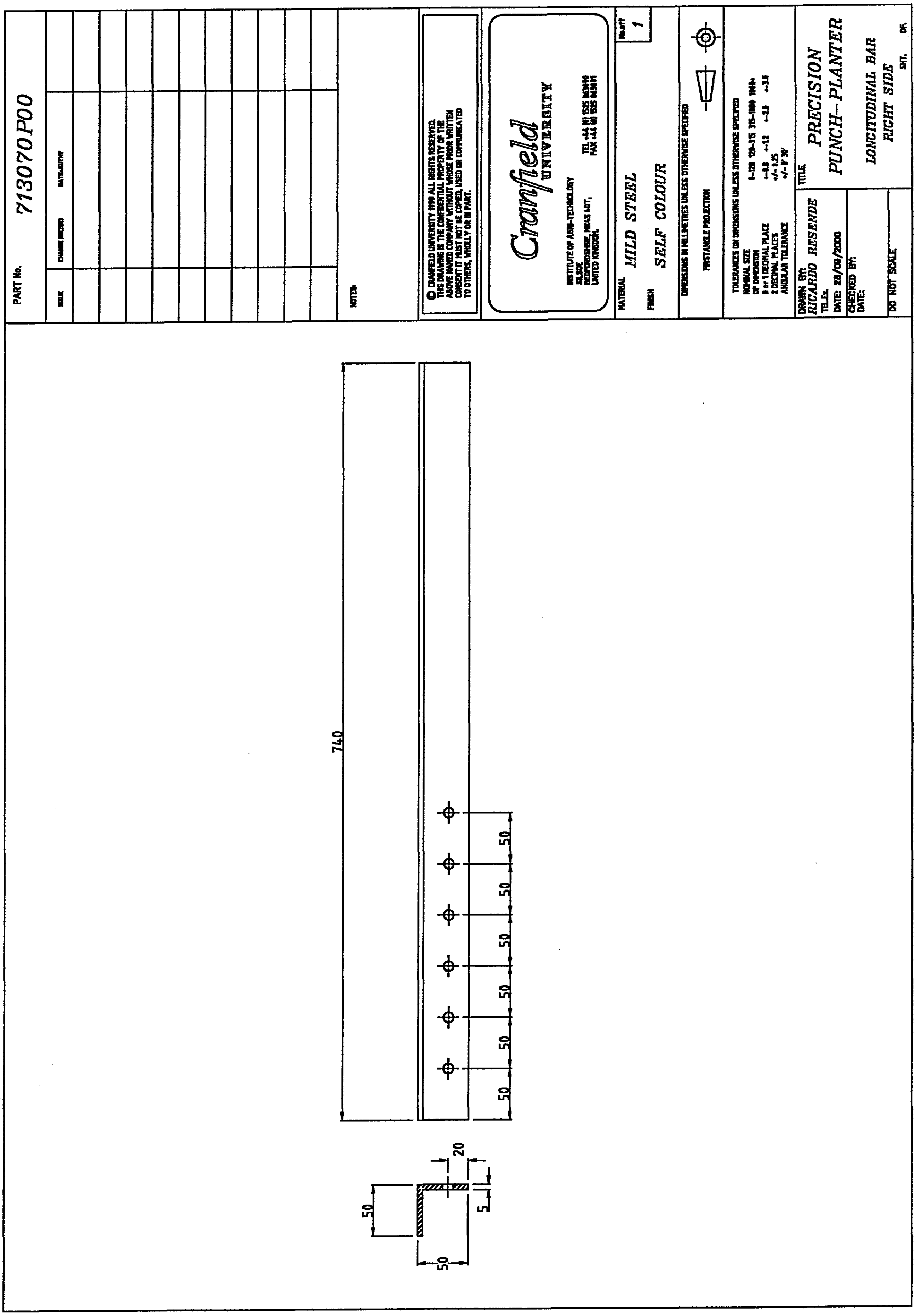
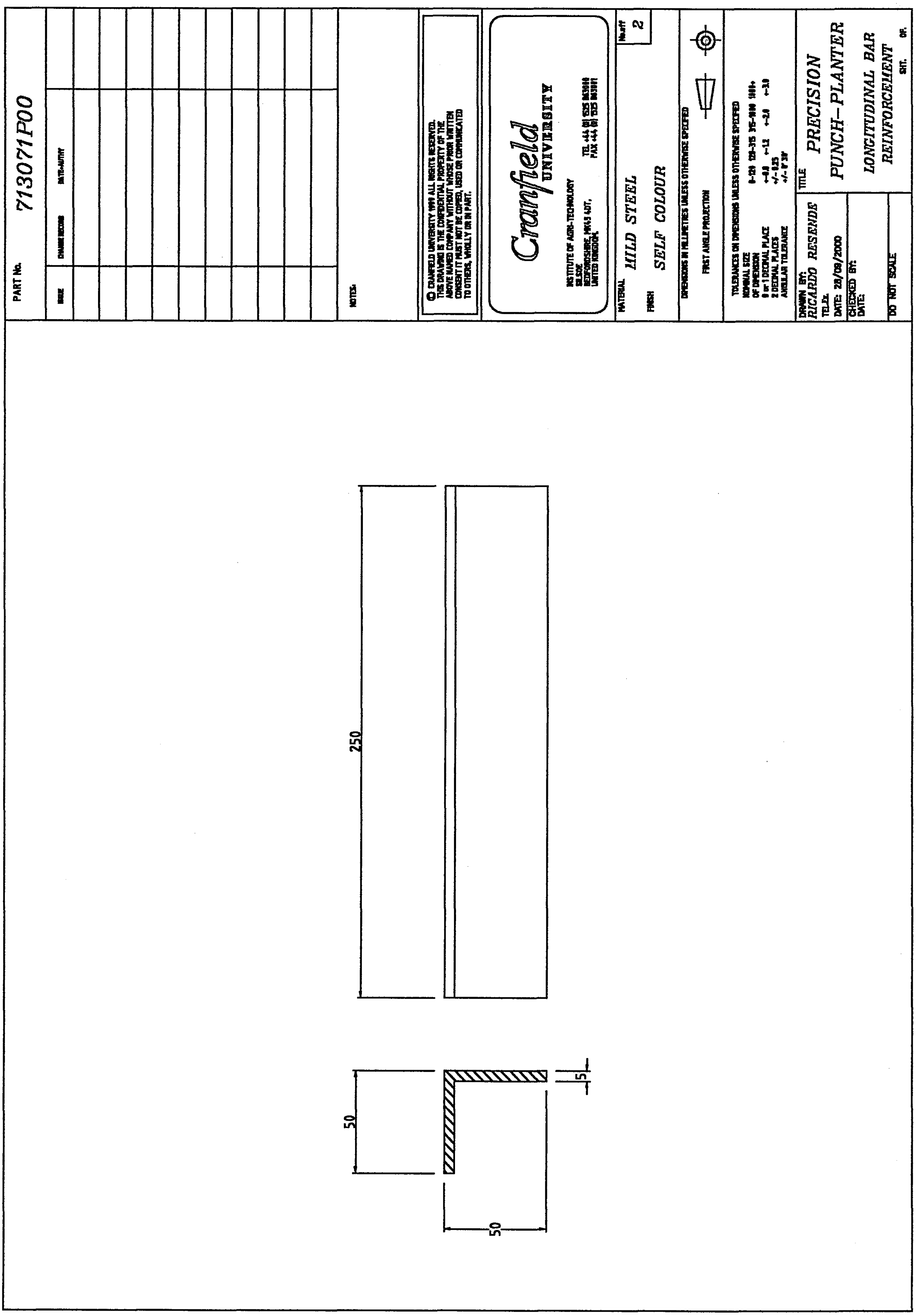
SILSOE
BEDFORDSHIRE, MK45 4DT,
UNITED KINGDOM.
MATERIAL MILD STEEL
No. off 1
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
TOLERANCES ON DIMENSIONS UNLESS OTHERWISE SPECIFIED
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE PRECISION PUNCH-PLANTER
LONGITUDINAL BAR LEFT SIDE
SHT. OF.
740
50
50
50
50
50
50
50
50
20
5


PART No.
713070P00
NOTES:
Cranfield
UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
1
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE 28/09/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE
PRECISION
PUNCH-PLANTER
LONGITUDINAL BAR
RIGHT SIDE
740
50
50
50
50
50
50
20
5
50
50


PART No.
713071P00
NOTES:
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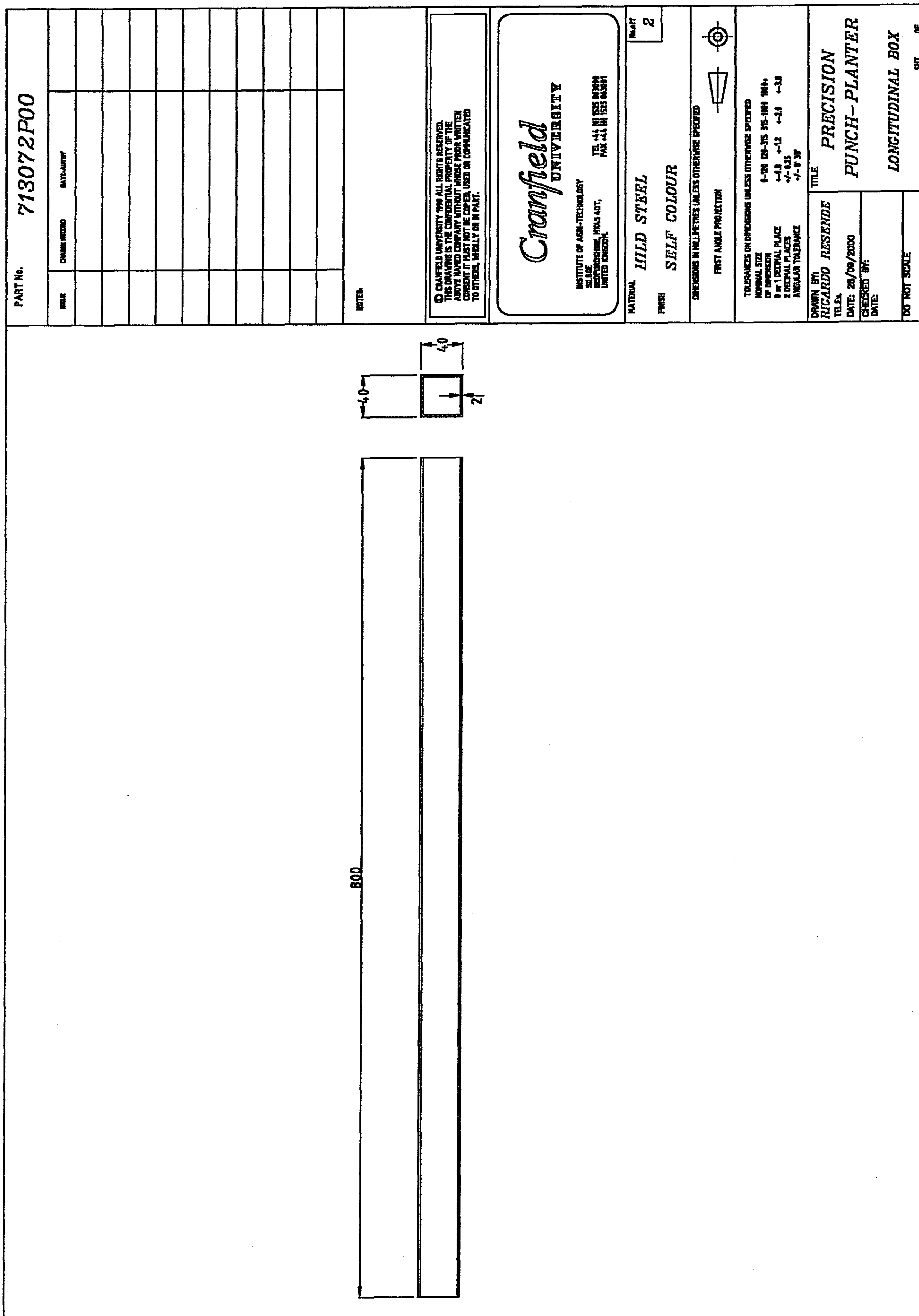
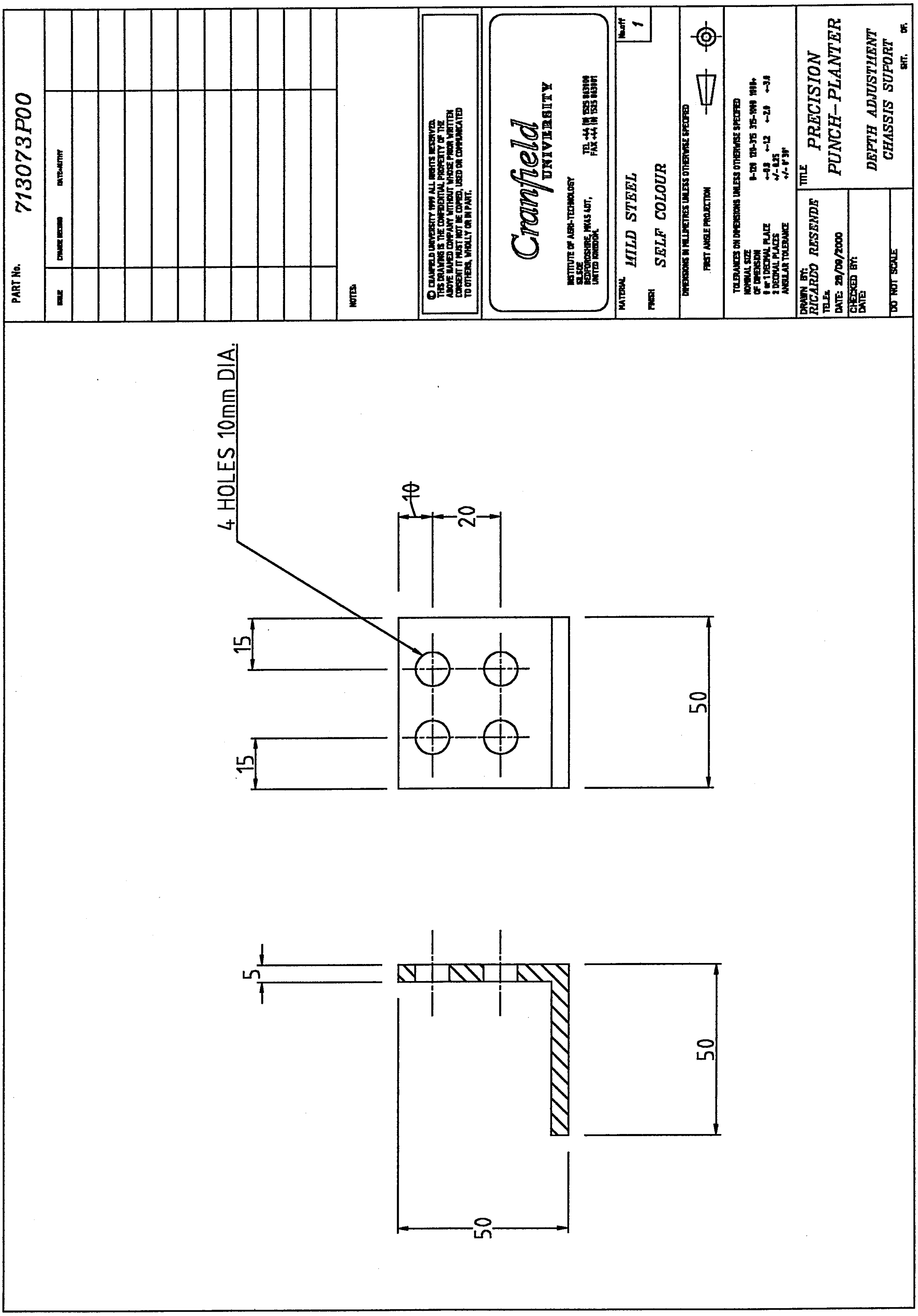
INSTITUTE OF AGRI-TECHNOLOGY
MATERIAL
MILD STEEL
FINISH
SELF COLOUR
No.off
2
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY:
RICARDO RESENDE
DATE: 28/08/2000
CHECKED BY:
DATE:
DO NOT SCALE
TITLE
PRECISION
PUNCH-PLANTER
LONGITUDINAL BAR
REINFORCEMENT
250
50
50
5


PART No.
713072P00
NOTES:
Cranfield UNIVERSITY
MATERIAL MILD STEEL
FINISH SELF COLOUR
No.off 2
FIRST ANGLE PROJECTION
TITLE
PRECISION PUNCH-PLANTER
LONGITUDINAL BOX
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
CHECKED BY:
DO NOT SCALE
40
40
2
800


PART No. 713073P00
NOTES:
Cranfield UNIVERSITY
INSTITUTE OF AERO-TECHNOLOGY
MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY: RICARDO RESENDE
DATE: 28/09/2000
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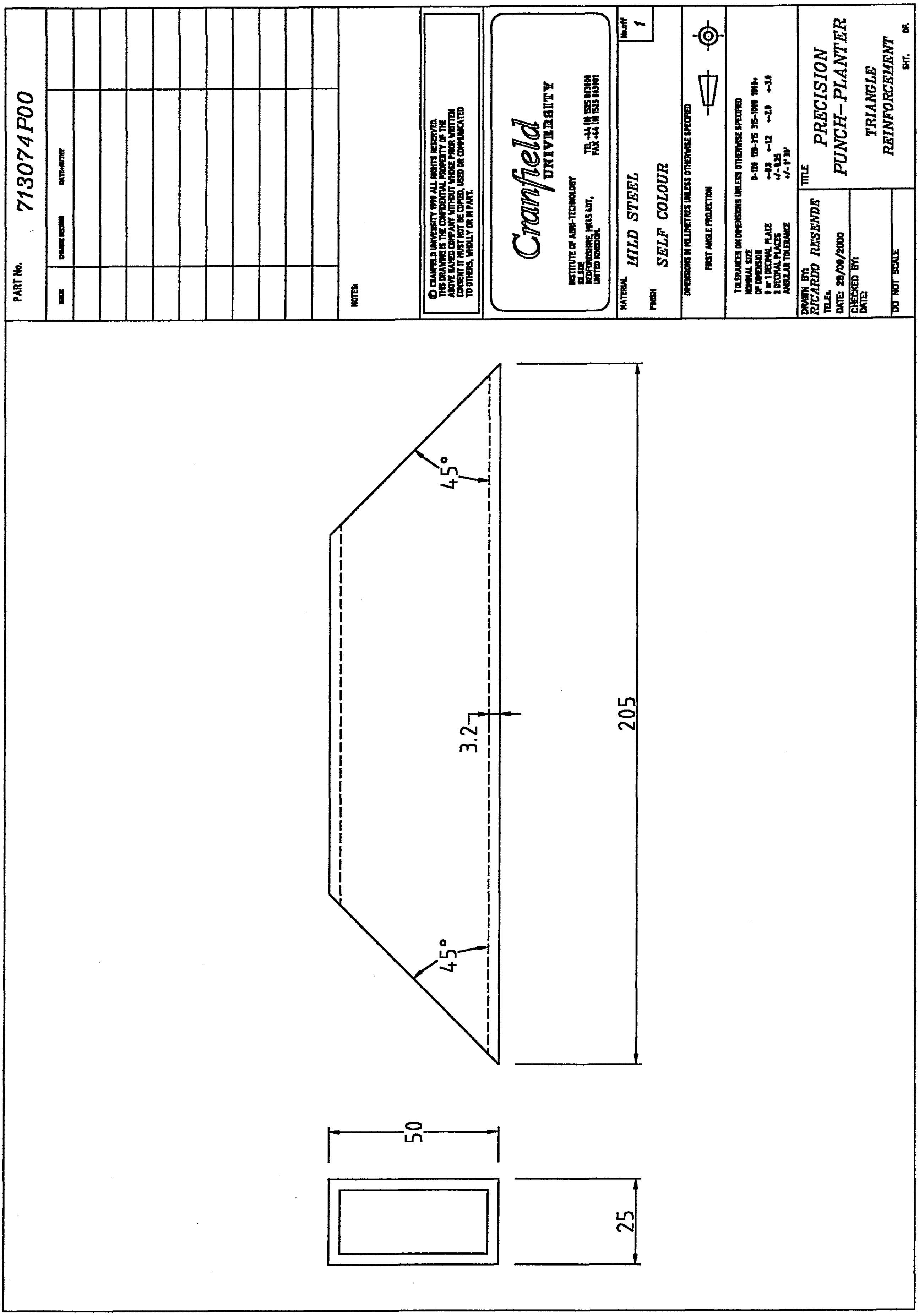
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MATERIAL MILD STEEL
FINISH SELF COLOUR
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
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DRAWN BY: RICARDO RESENDE
DATE: 28/08/2000
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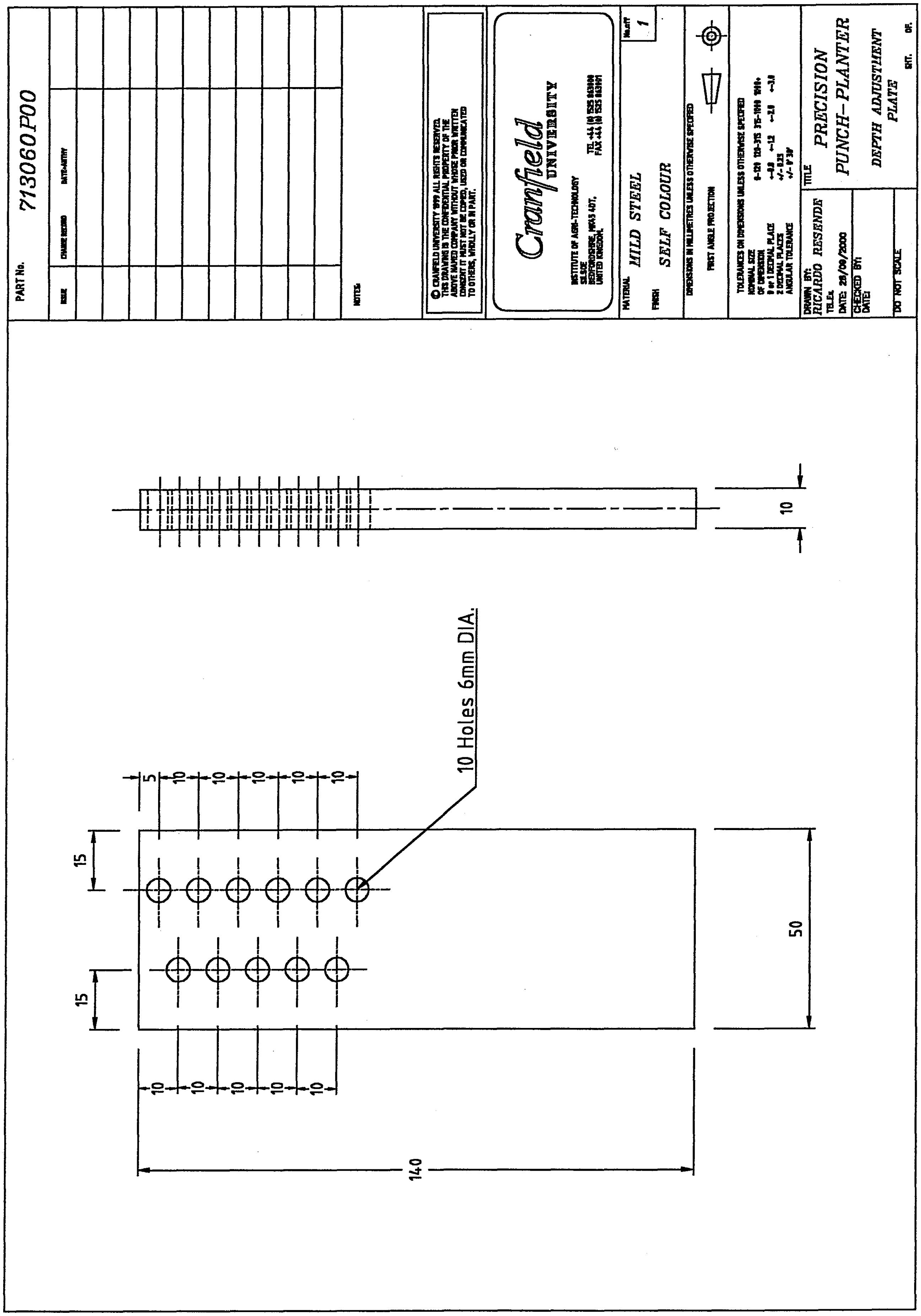
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DATE 25/09/2000
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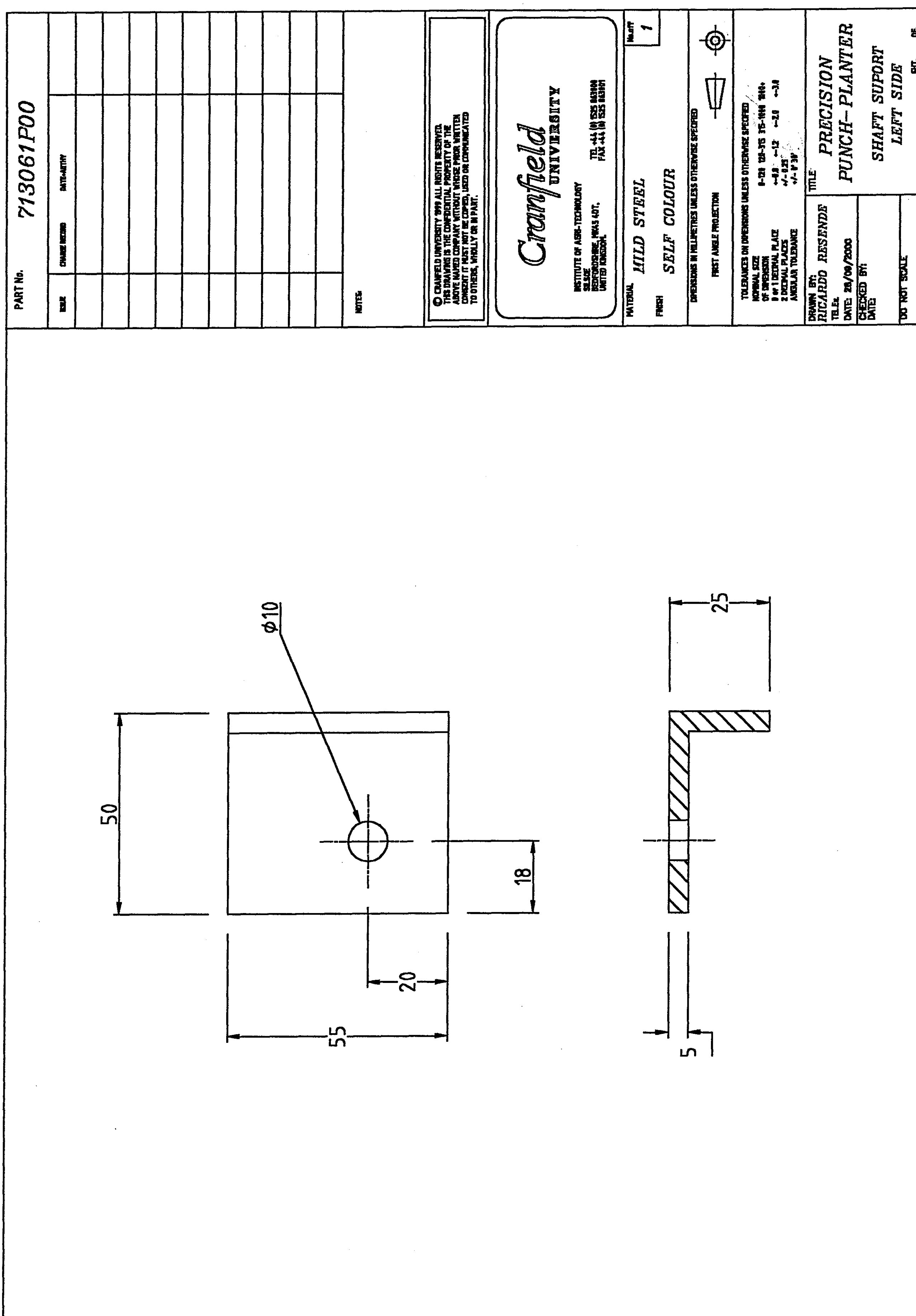
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DRAWN BY: RICARDO RESENDE
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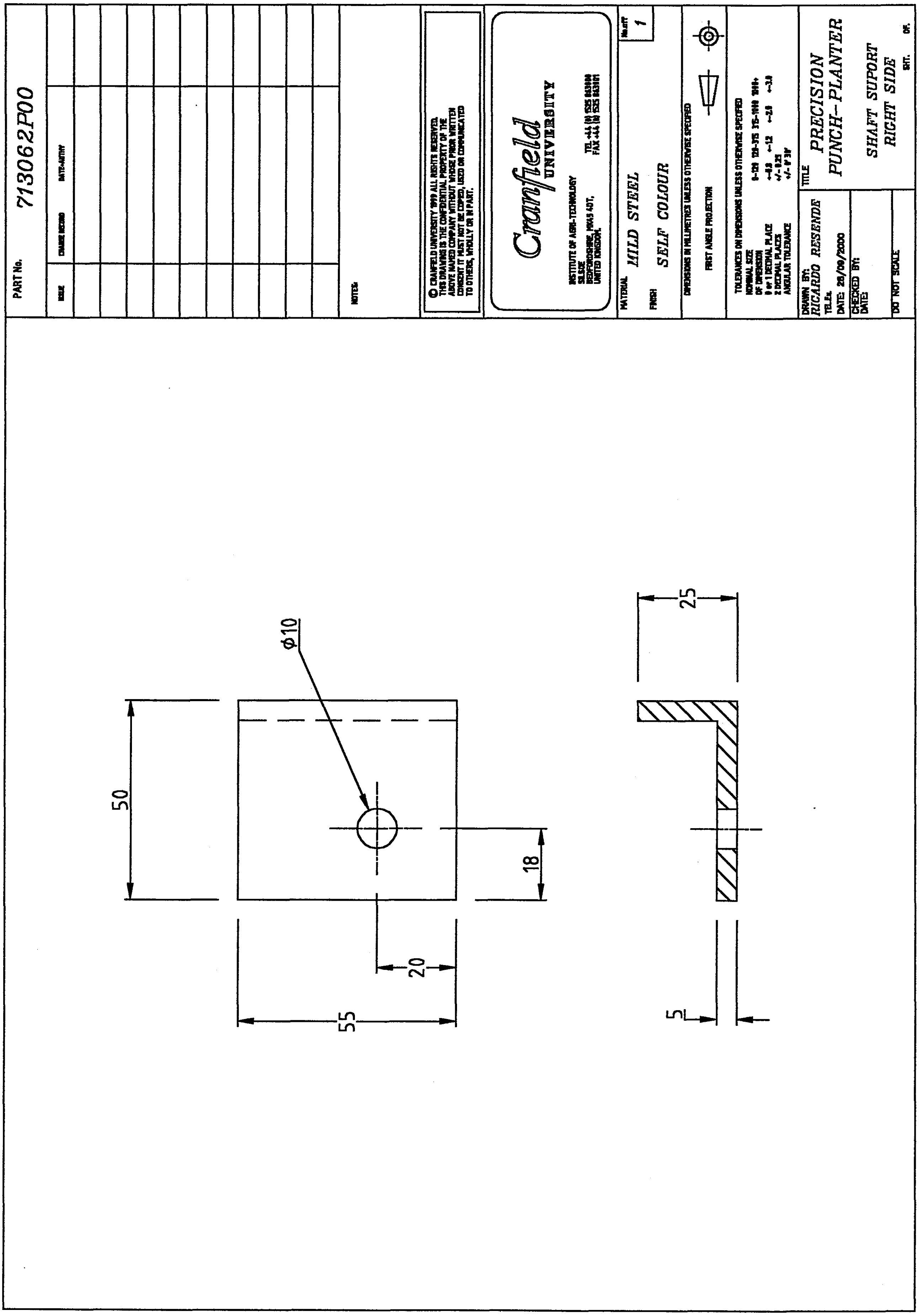

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INSTITUTE OF AGRI-TECHNOLOGY
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DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE SPECIFIED
FIRST ANGLE PROJECTION
DRAWN BY:
RICARDO RESENDE
DATE: 28/06/2000
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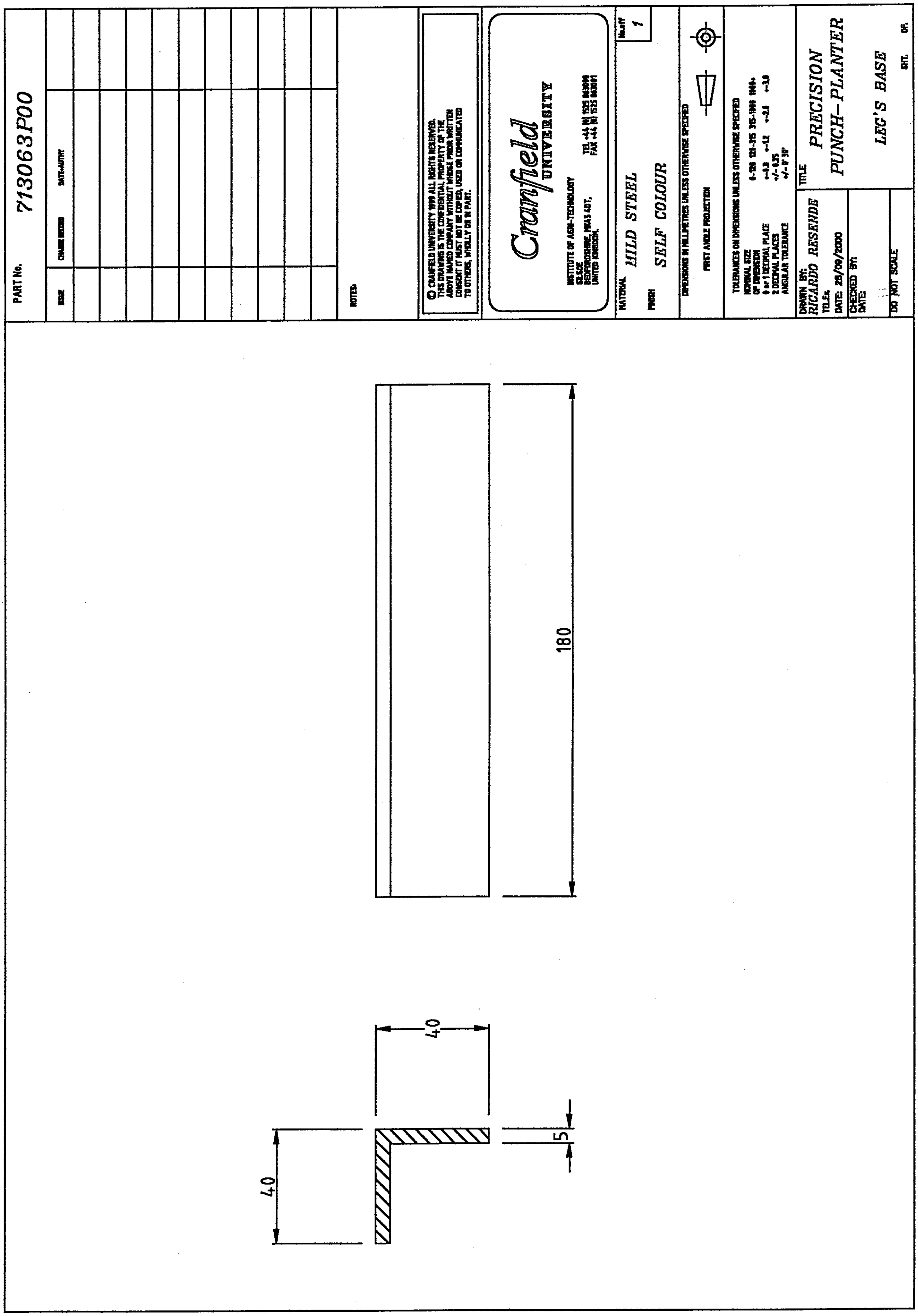
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INSTITUTE OF AGRI-TECHNOLOGY
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DRAWN BY: RICARDO RESENDE
DATE: 25/09/2000
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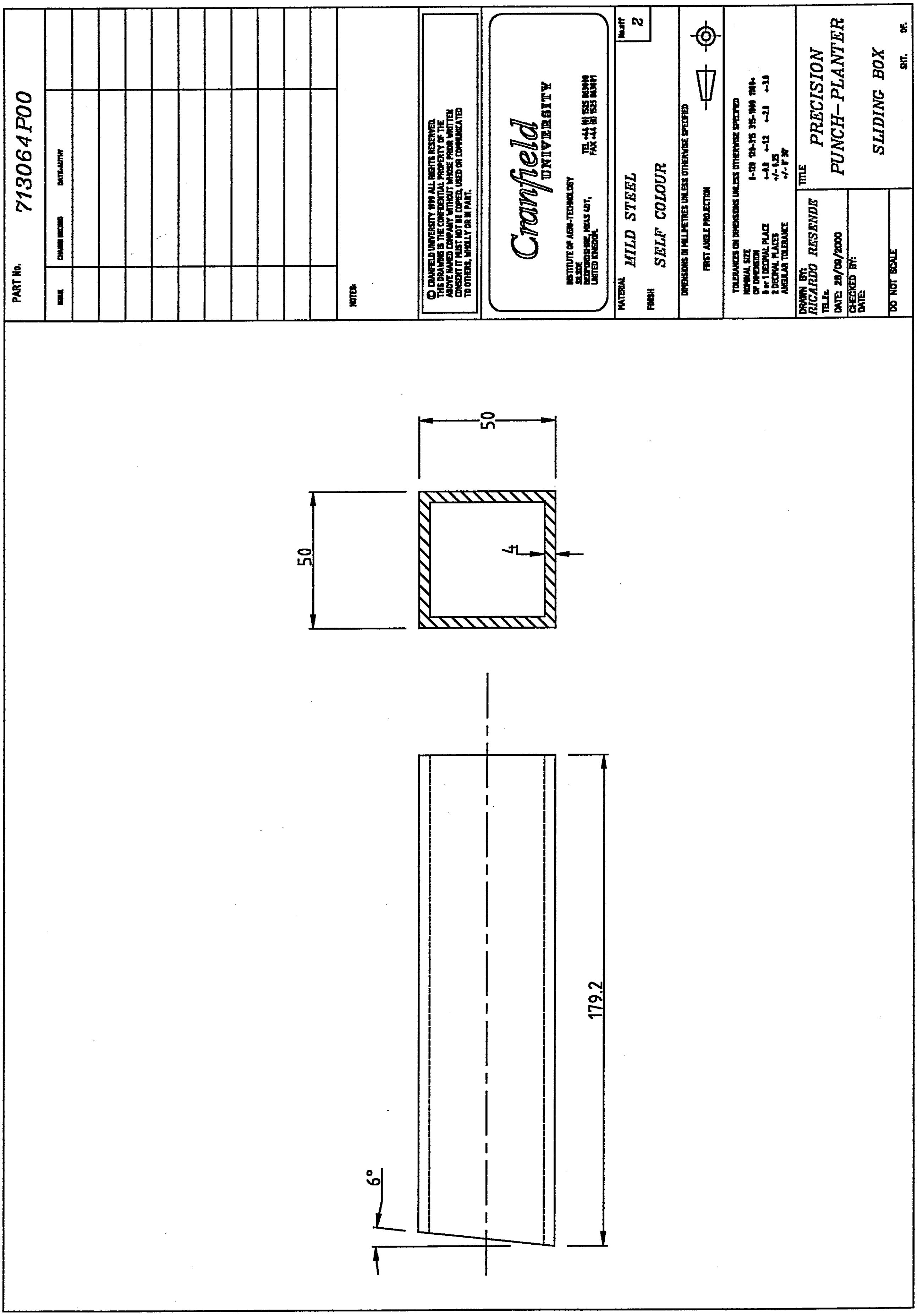
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FINISH SELF COLOUR
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DATE: 28/08/2000
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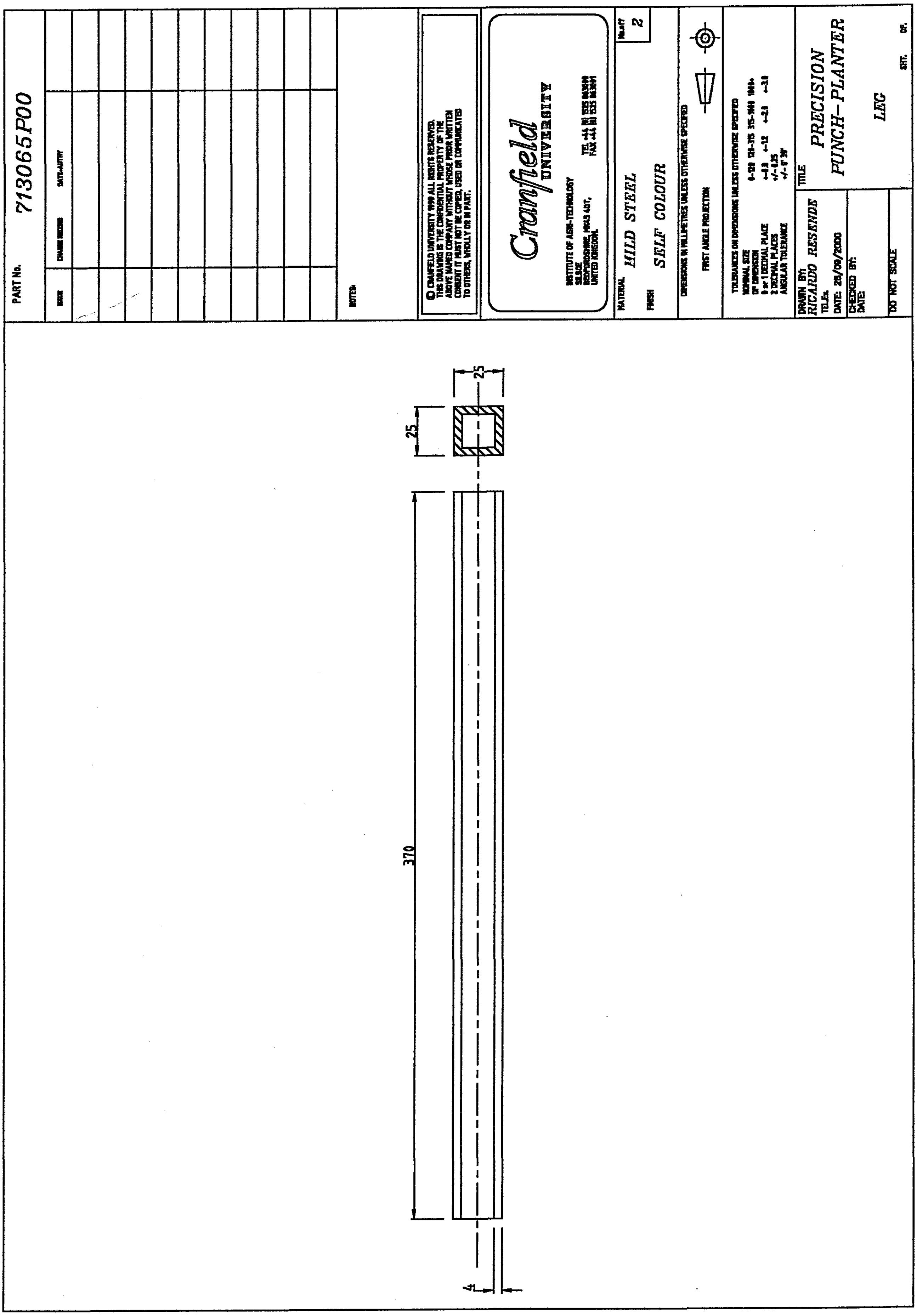
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Appendix C

Analysis of variance - ANOVA

C.1. Analysis of an unbalanced design using GenStat regression

The analysis of variance for seed spacing, seed spacing around the target and seed depth were done using unbalanced design, because the number of measurements varied for seed and speed.

C.1.1. Regression analysis for seed spacing

Variate: Seed spacing
"Unbalanced Treatment Structure."
BLOCK Replication
TREATMENTS Speed*Seed
COVARIATE "No Covariate"
LSD level = 5 %

Table C.1: Accumulated analysis of variance for seed spacing.

Change	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
+ Replication	2	1270.8	635.4	5.24	0.006
+ Speed	2	1793.0	896.5	7.39	<.001
+ Seed	1	2525.2	2525.2	20.81	<.001
+Speed*seed	2	1672.2	836.1	6.89	0.001
Residual	563	68321.2	121.4		
Total	570	75582.3	132.6		

Table C.2: Seed spacing predictions from regression model for speed.

Speed (km/h)	**Prediction (cm)**	**Se (cm)**
4	20.675	0.730
6	22.374	0.843
8	25.727	0.856

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Table C.3: Standard errors of differences between pairs of predicted means for speed.

Speed (km/h)	**4**	**6**	**8**
4	*		
6	1.115	*	
8	1.125	1.201	*

Rows and columns are labelled by the labels/levels of the factors: speed

Minimum standard error of differences	1.115
Average standard error of differences	1.147
Maximum standard error of differences	1.201

Table C.4: Least significant differences (at 5.0%) for predicted means for speed.

Speed (km/h)	4	6	8
4	*		
6	2.190	*	
8	2.210	2.359	*

Rows and columns are labelled by the labels/levels of the factors: speed

Minimum least significant difference 2.190
Average least significant difference 2.253
Maximum least significant difference 2.359

Table C.5: Seed spacing predictions from regression model for seed.

	Prediction	se
Seed		
Sugar beet	20.751	0.621
Wheat	25.123	0.698

Standard error of differences between predicted means 0.9342
Least significant difference (at 5.0%) for predicted means 1.835

Table C.6: Seed spacing predictions from regression model for speed and seed.

	Sugar beet		Wheat	
Speed (km/h)	Prediction	se	Prediction	se
4	20.30	1.02	21.14	1.03
6	20.50	1.14	24.72	1.26
8	21.61	1.06	30.91	1.40

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Table C.7: Standard errors of differences between pairs of predicted means for speed and seed.

	4 km/h Sugar beet	4 km/h Wheat	6 km/h Sugar beet	6 km/h Wheat	8 km/h Sugar beet	8 km/h Wheat
4 km/h Sugar beet	*					
4 km/h Wheat	1.453	*				
6 km/h Sugar beet	1.530	1.537	*			
6 km/h Wheat	1.622	1.626	1.693	*		
8 km/h Sugar beet	1.473	1.480	1.556	1.645	*	
8 km/h Wheat	1.733	1.738	1.805	1.881	1.756	*

Rows and columns are labelled by the labels/levels of the factors: speed and seed

Minimum standard error of differences 1.453
Average standard error of differences 1.635
Maximum standard error of differences 1.881

Table C.8: Least significant differences (at 5.0%) for predicted means for speed and seed.

	4 km/h Sugar beet	**4 km/h Wheat**	**6 km/h Sugar beet**	**6 km/h Wheat**	**8 km/h Sugar beet**	**8 km/h Wheat**
4 km/h Sugar beet	*					
4 km/h Wheat	2.854	*				
6 km/h Sugar beet	3.006	3.019	*			
6 km/h Wheat	3.187	3.195	3.326	*		
8 km/h Sugar beet	2.894	2.906	3.056	3.231	*	
8 km/h Wheat	3.404	3.415	3.545	3.694	3.448	*

Rows and columns are labelled by the labels/levels of the factors: speed and seed

Minimum least significant difference 2.854
Average least significant difference 3.212
Maximum least significant difference 3.694

Table C.9: Coefficient of variation and standard error of a single unit

cv (%)	**se**
48.96	11.02

C.1.2. Regression analysis for seed spacing around the target

Variate: Seed spacing around the target
"Unbalanced Treatment Structure."
BLOCK Replication
TREATMENTS Speed*Seed
COVARIATE "No Covariate"
LSD level = 5 %

Table C.10: Accumulated analysis of variance for seed spacing around the target.

Change	**d.f**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
+ Replication	2	4.026	2.013	0.42	0.655
+ Speed	2	0.806	0.403	0.08	0.919
+ Seed	1	0.405	0.405	0.09	0.771
+Speed*seed	2	11.052	5.526	1.16	0.313
Residual	462	2194.906	4.751		
Total	469	2211.195	4.715		

Table C.11: Seed spacing predictions from regression model for speed considering only seed spacing around the target.

	Prediction	**se**
Speed (km/h)		
4	18.474	0.154
6	18.486	0.184
8	18.438	0.205

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Table C.12: Standard errors of differences between pairs of predicted means for speed considering only seed spacing around the target.

Speed (km/h)	**4**	**6**	**8**
4	*		
6	0.2392	*	
8	0.2557	0.2752	*

Rows and columns are labelled by the labels/levels of the factors: speed

Minimum standard error of differences 0.2392
Average standard error of differences 0.2567
Maximum standard error of differences 0.2752

Table C.13: Least significant differences (at 5.0%) for predicted means for speed considering only seed spacing around the target.

Speed (km/h)	**4**	**6**	**8**
4	*		
6	0.4701	*	
8	0.5026	0.5409	*

Rows and columns are labelled by the labels/levels of the factors: speed

Minimum least significant difference 0.4701
Average least significant difference 0.5045
Maximum least significant difference 0.5409

Table C.14: Seed spacing predictions from regression model for seed considering only seed spacing around the target.

	Prediction	se
Seed		
Sugar beet	18.434	0.132
Wheat	18.518	0.161

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Standard error of differences between predicted means 0.2079
Least significant difference (at 5.0%) for predicted means 0.4086

Table C.15: Seed spacing predictions from regression model for speed and seed considering only seed spacing around the target.

	Sugar beet		Wheat	
Speed (km/h)	**Prediction**	**se**	**Prediction**	**se**
4	18.582	0.212	18.320	0.217
6	18.391	0.239	18.624	0.289
8	18.235	0.234	18.730	0.369

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Table C.16: Standard errors of differences between pairs of predicted means for speed and seed considering only seed spacing around the target.

	4 km/h Sugar beet	**4 km/h Wheat**	**6 km/h Sugar beet**	**6 km/h Wheat**	**8 km/h Sugar beet**	**8 km/h Wheat**
4 km/h Sugar beet	*					
4 km/h Wheat	0.3035	*				
6 km/h Sugar beet	0.3187	0.3223	*			
6 km/h Wheat	0.3588	0.3615	0.3741	*		
8 km/h Sugar beet	0.3154	0.3188	0.3343	0.3715	*	
8 km/h Wheat	0.4252	0.4280	0.4397	0.4685	0.4370	*

Rows and columns are labelled by the labels/levels of the factors: speed and seed

Minimum standard error of differences 0.3035
Average standard error of differences 0.3718
Maximum standard error of differences 0.4685

Table C.17: Least significant differences (at 5.0%) for predicted means for speed and seed considering only seed spacing around the target.

	4 km/h Sugar beet	4 km/h Wheat	6 km/h Sugar beet	6 km/h Wheat	8 km/h Sugar beet	8 km/h Wheat
4 km/h Sugar beet	*					
4 km/h Wheat	0.5964	*				
6 km/h Sugar beet	0.6262	0.6333	*			
6 km/h Wheat	0.7050	0.7105	0.7352	*		
8 km/h Sugar beet	0.6198	0.6265	0.6569	0.7301	*	
8 km/h Wheat	0.8356	0.8410	0.8641	0.9207	0.8588	*

Rows and columns are labelled by the labels/levels of the factors: speed and seed

Minimum least significant difference 0.5964
Average least significant difference 0.7307
Maximum least significant difference 0.9207

Table C.18: Coefficient of variation and standard error of a single unit

cv (%)	se
11.82	2.180

C.1.3. Regression analysis for seed depth

Variate: Seed depth
"Unbalanced Treatment Structure."
BLOCK Replication
TREATMENTS Speed*Seed
COVARIATE "No Covariate"
LSD level = 5 %

Table C.19: Accumulated analysis of variance for seed depth.

Change	d.f	s.s.	m.s.	v.r.	F pr.
+ Replication	2	60.64	30.32	1.82	0.163
+ Speed	2	34.61	17.31	1.04	0.354
+ Seed	1	365.41	365.41	21.95	<.001
+Speed*seed	2	10.31	5.16	0.31	0.734
Residual	563	9373.55	16.65		
Total	570	9844.53	17.27		

Table C.20: Seed depth predictions from regression model for speed.

	Prediction	se
Speed (km/h)		
4	30.009	0.271
6	30.089	0.312
8	29.313	0.317

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Table C.21: Standard errors of differences between pairs of predicted means for speed.

Speed (km/h)	4	6	8
4			
6	0.4131		
8	0.4168	0.4449	

Rows and columns are labelled by the labels/levels of the factors: speed

Table C.22: Least significant differences (at 5.0%) for predicted means for speed.

Speed (km/h)	4	6	8
4			
6	0.8113		
8	0.8187	0.8739	

Rows and columns are labelled by the labels/levels of the factors: speed

Table C.23: Seed depth predictions from regression model for seed.

	Prediction	se
Seed		
Sugar beet	30.547	0.230
Wheat	28.919	0.259

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Standard error of differences between predicted means 0.3460
Least significant difference (at 5.0%) for predicted means 0.6796

Table C.24: Seed depth predictions from regression model for speed and seed.

	Sugar beet		Wheat	
Speed (km/h)	Prediction	se	Prediction	se
4	30.722	0.379	29.111	0.382
6	30.658	0.422	29.374	0.466
8	30.198	0.393	28.202	0.518

The standard errors are appropriate for interpretation of the predictions as summaries of the data rather than as forecasts of new observations.

Table C.25: Standard errors of differences between pairs of predicted means for speed and seed.

	4 km/h Sugar beet	**4 km/h Wheat**	**6 km/h Sugar beet**	**6 km/h Wheat**	**8 km/h Sugar beet**	**8 km/h Wheat**
4 km/h Sugar beet	*					
4 km/h Wheat	0.5382	*				
6 km/h Sugar beet	0.5668	0.5694	*			
6 km/h Wheat	0.6009	0.6025	0.6273	*		
8 km/h Sugar beet	0.5457	0.5480	0.5763	0.6093	*	
8 km/h Wheat	0.6419	0.6439	0.6685	0.6966	0.6503	*

Rows and columns are labelled by the labels/levels of the factors: speed and seed

Table C.26: Least significant differences (at 5.0%) for predicted means for speed and seed.

	4 km/h Sugar beet	**4 km/h Wheat**	**6 km/h Sugar beet**	**6 km/h Wheat**	**8 km/h Sugar beet**	**8 km/h Wheat**
4 km/h Sugar beet	*					
4 km/h Wheat	1.057	*				
6 km/h Sugar beet	1.113	1.118	*			
6 km/h Wheat	1.180	1.183	1.232	*		
8 km/h Sugar beet	1.072	1.076	1.132	1.197	*	
8 km/h Wheat	1.261	1.265	1.313	1.368	1.277	*

Rows and columns are labelled by the labels/levels of the factors: speed and seed

Table C.27: Coefficient of variation and standard error of a single unit

cv (%)	**se**
13.68	4.080

C.2. Two-way ANOVA in randomised blocks using GenStat regression

The analysis of variance for quality of feed index – A, multiple index – D, missing index – M, coefficient of precision – CP3 and precision – C were done in randomised blocks. These indexes were calculated for every replication prior to this analysis.

C.2.1. Regression analysis for quality of feed index - A

""Two-way ANOVA (in Randomised Blocks).""
BLOCK Replication
TREATMENTS Seed*Speed
COVARIATE ""No Covariate""
LSDLEVEL=5

Table C.28: Analysis of variance for seed depth.

Source of variation	d.f	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	425.04	212.52	3.94	
Replication.*Units* stratum					
Seed	1	850.93	850.93	15.77	0.003
Speed	2	1505.78	752.89	13.96	0.001
Seed.Speed	2	361.89	180.95	3.35	0.077
Residual	10	539.51	53.95		
Total	17	3683.15			

Table C.29: Mean quality of feed index for seed.

Seed	Sugar beet	Wheat
	86.6	72.9

Table C.30: Mean quality of feed index for speed.

Speed (km/h)	4	6	8
	90.1	81.3	67.9

Table C.31: Mean quality of feed index for speed and seed.

	Speed (km/h)		
Seed	**4**	**6**	**8**
Sugar beet	91.4	88.4	80.1
Wheat	88.8	74.3	55.6

Grand mean:79.8

Table C.32: Standard errors of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
e.s.e.	2.45	3.00	4.24

Table C.33: Standard errors of differences of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
s.e.d.	3.46	4.24	6.00

Table C.34: Least significant differences of means (5% level).

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
l.s.d.	7.71	9.45	13.36

Table C.35:. Stratum standard errors and coefficients of variation.

Stratum	d.f.	s.e.	cv (%)
replication.	2	5.95	7.5
Replication. *Units*	10	7.35	9.2

C.2.2. Regression analysis for multiple index - D

""Two-way ANOVA (in Randomised Blocks).""
BLOCK Replication
TREATMENTS Seed*Speed
COVARIATE ""No Covariate""
LSDLEVEL=5

Table C.36: Analysis of variance for multiple index - D.

Source of variation	d.f	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	8.216	4.108	0.92	
Replication.*Units* stratum					
Seed	1	4.136	4.136	0.92	0.359
Speed	2	6.060	3.030	0.68	0.530
Seed.Speed	2	4.291	2.145	0.48	0.633
Residual	10	44.731	4.473		
Total	17	67.434			

Table C.37: Mean multiple index for seed.

Seed	Sugar beet	Wheat
	0.34	1.3

Table C.38: Mean multiple index for speed.

Speed (km/h)	4	6	8
	0	1.15	1.30

Table C.39: Mean multiple index for speed and seed.

	Speed (km/h)		
Seed	**4**	**6**	**8**
Sugar beet	0	0	1.01
Wheat	0	2.3	1.59

Grand mean 0.82

Table C.40: Standard errors of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
e.s.e.	0.705	0.863	1.221

Table C.41: Standard errors of differences of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
s.e.d.	0.997	1.221	1.727

Table C.42: Least significant differences of means (5% level).

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
l.s.d.	2.221	2.721	3.848

Table C.43:. Stratum standard errors and coefficients of variation.

Stratum	d.f.	s.e.	cv (%)
replication.	2	0.827	101.4
Replication. *Units*	10	2.115	259.2

C.2.3. Regression analysis for missing index - M

""Two-way ANOVA (in Randomised Blocks).""
BLOCK Replication
TREATMENTS Seed*Speed
COVARIATE ""No Covariate""
LSDLEVEL=5

Table C.44: Analysis of variance for missing index - M.

Source of variation	d.f	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	338.60	169.30	3.85	
Replication.*Units* stratum					
Seed	1	736.42	736.42	16.77	0.002
Speed	2	1347.96	673.98	15.35	<.001
Seed.Speed	2	345.10	172.55	3.93	0.055
Residual	10	439.17	43.92		
Total	17	3207.25			

Table C.45: Mean missing index for seed.

Seed	Sugar beet	Wheat
	13.0	25.8

Table C.46: Mean missing index for speed.

Speed (km/h)	4	6	8
	9.9	17.5	30.8

Table C.47: Mean missing index for speed and seed.

	Speed (km/h)		
Seed	**4**	**6**	**8**
Sugar beet	8.6	11.6	18.8
Wheat	11.2	23.4	42.8

Grand mean: 19.4

Table C.48: Standard errors of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
e.s.e.	2.21	2.71	3.83

Table C.49: Standard errors of differences of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
s.e.d.	3.12	3.83	5.41

Table C.50: Least significant differences of means (5% level).

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
l.s.d.	6.96	8.53	12.06

Table C.51:. Stratum standard errors and coefficients of variation.

Stratum	d.f.	s.e.	cv (%)
replication.	2	5.31	27.4
Replication. *Units*	10	6.63	34.1

C.2.4. Regression analysis for coefficient of precision - CP3

""Two-way ANOVA (in Randomised Blocks).""
BLOCK Replication
TREATMENTS Seed*Speed
COVARIATE ""No Covariate""
LSDLEVEL=5

Table C.52: Analysis of variance for coefficient of precision - CP3.

Source of variation	d.f	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	493.87	246.94	3.34	
Replication.*Units* stratum					
Seed	1	765.40	765.4	10.37	0.009
Speed	2	892.80	446.4	6.05	0.019
Seed.Speed	2	1058.56	529.28	7.17	0.012
Residual	10	738.32	73.83		
Total	17	3948.96			

Table C.53: Mean coefficient of precision for seed.

Seed	Sugar beet	Wheat
	53.2	40.2

Table C.54: Mean coefficient of precision for speed.

Speed (km/h)	4	6	8
	56.4	40.1	43.5

Table C.55: Mean coefficient of precision for speed and seed.

	Speed (km/h)		
Seed	**4**	**6**	**8**
Sugar beet	56.9	41.9	60.8
Wheat	56.0	38.3	26.2

Grand mean:46.7

Table C.56: Standard errors of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
e.s.e.	2.86	3.51	4.96

Table C.57: Standard errors of differences of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
s.e.d.	4.05	4.96	7.02

Table C.58: Least significant differences of means (5% level).

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
l.s.d.	9.03	11.05	15.63

Table C.59: Stratum standard errors and coefficients of variation.

Stratum	d.f.	s.e.	cv (%)
replication.	2	6.42	13.7
Replication. *Units*	10	8.59	18.4

C.2.5. Regression analysis for precision - C

""Two-way ANOVA (in Randomised Blocks).""
BLOCK Replication
TREATMENTS Seed*Speed
COVARIATE ""No Covariate""
LSDLEVEL=5

Table C.60: Analysis of variance for precision - C.

Source of variation	d.f	s.s.	m.s.	v.r.	F pr.
Replication stratum	2	25.839	12.919	1.73	
Replication.*Units* stratum					
Seed	1	10.820	10.820	1.45	0.256
Speed	2	4.885	2.442	0.33	0.728
Seed.Speed	2	18.993	9.497	1.27	0.321
Residual	10	74.498	7.450		
Total	17	135.034			

Table C.61: Mean precision for seed.

Seed	Sugar beet	Wheat
	11.40	12.95

Table C.62: Mean precision for speed.

Speed (km/h)	4	6	8
	11.55	12.82	12.15

Table C.63: Mean precision for speed and seed.

	Speed (km/h)		
Seed	4	6	8
Sugar beet	10.68	13.34	10.16
Wheat	12.41	12.30	14.13

Grand mean: 12.17

Table C.64: Standard errors of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
e.s.e.	0.910	1.114	1.576

Table C.65: Standard errors of differences of means.

Table	Seed	Speed	Seed Speed
rep.	9	6	3
d.f.	10	10	10
s.e.d.	1.287	1.576	2.229

Table C.66: Least significant differences of means (5% level).

Table	**Seed**	**Speed**	**Seed Speed**
rep.	9	6	3
d.f.	10	10	10
l.s.d.	2.867	3.511	4.966

Table C.67: Stratum standard errors and coefficients of variation.

Stratum	**d.f.**	**s.e.**	**cv (%)**
replication.	2	1.467	12.1
Replication. *Units*	10	2.729	22.4

Appendix D

Soil classification, bulk density and moisture content

Contents

D.1. Soil classification

Table D.1. Soil classification

Clay (%)	4.78
Silt (%)	2.51
Sand (%)	92.71
Textural Class	Sand

D.2. Soil Bulk Density

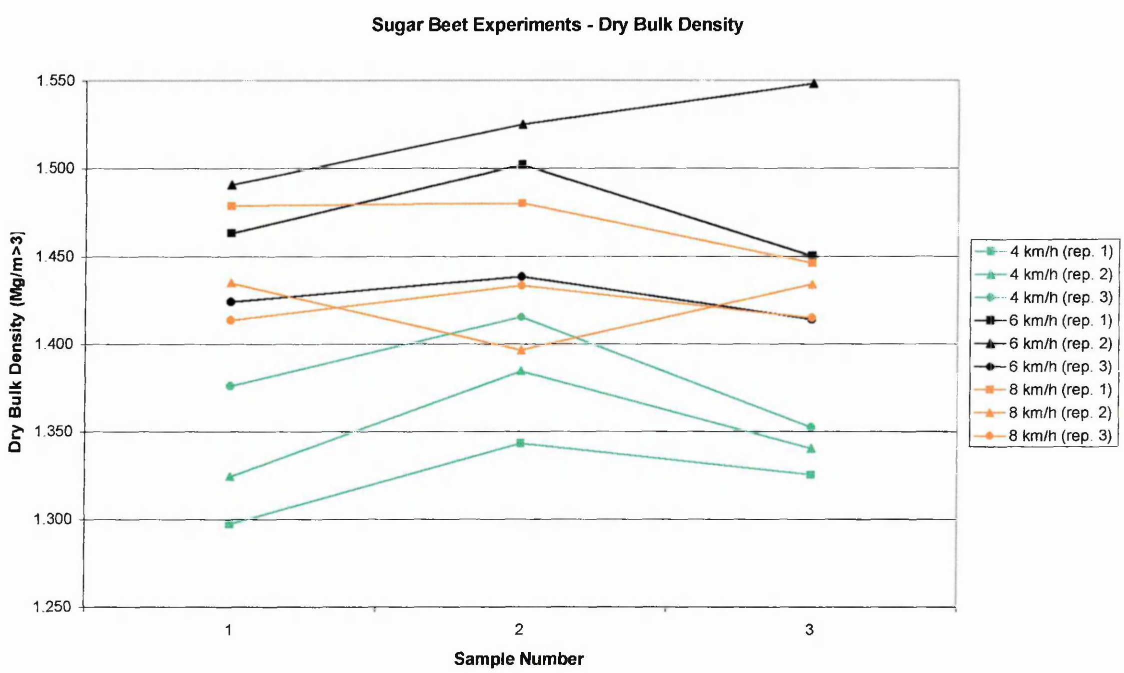

Figure D.1: Soil dry bulk density for the sugar beet experiments

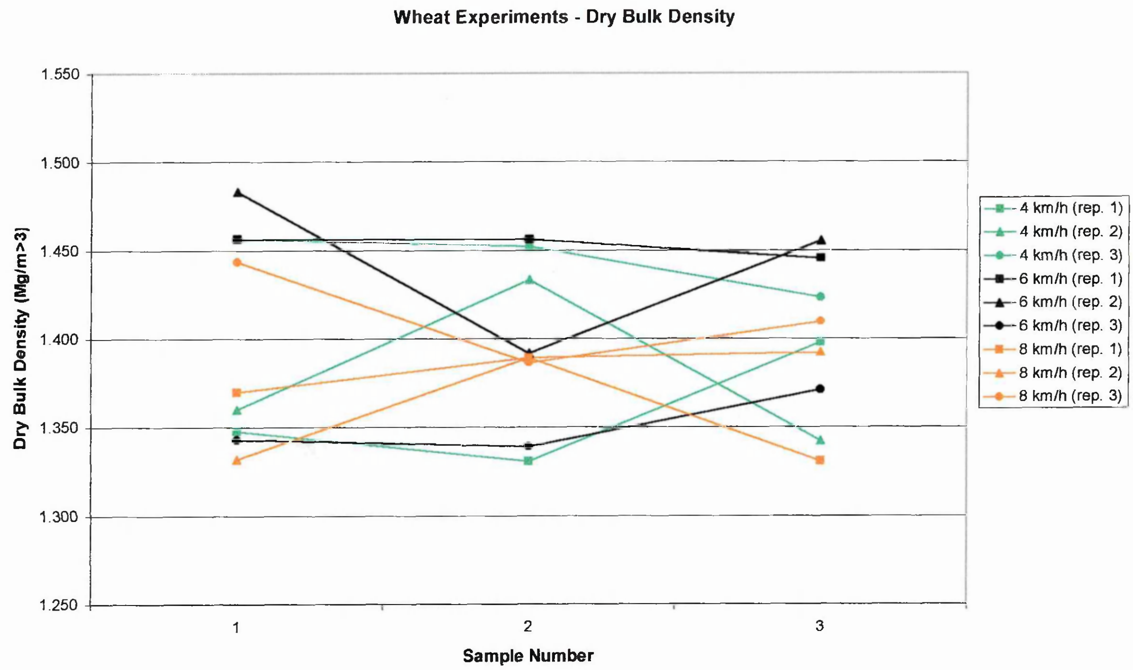

Figure D.2: Soil dry bulk density for the wheat experiments

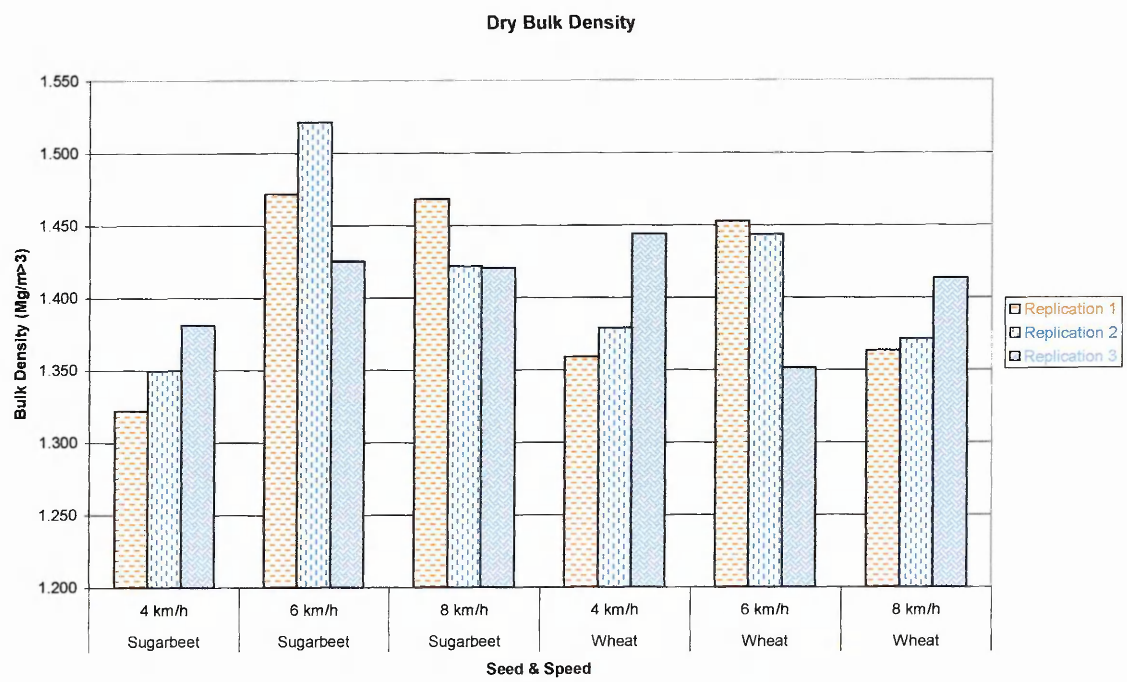

Figure D.3: Soil dry bulk density for seed, speed and replication

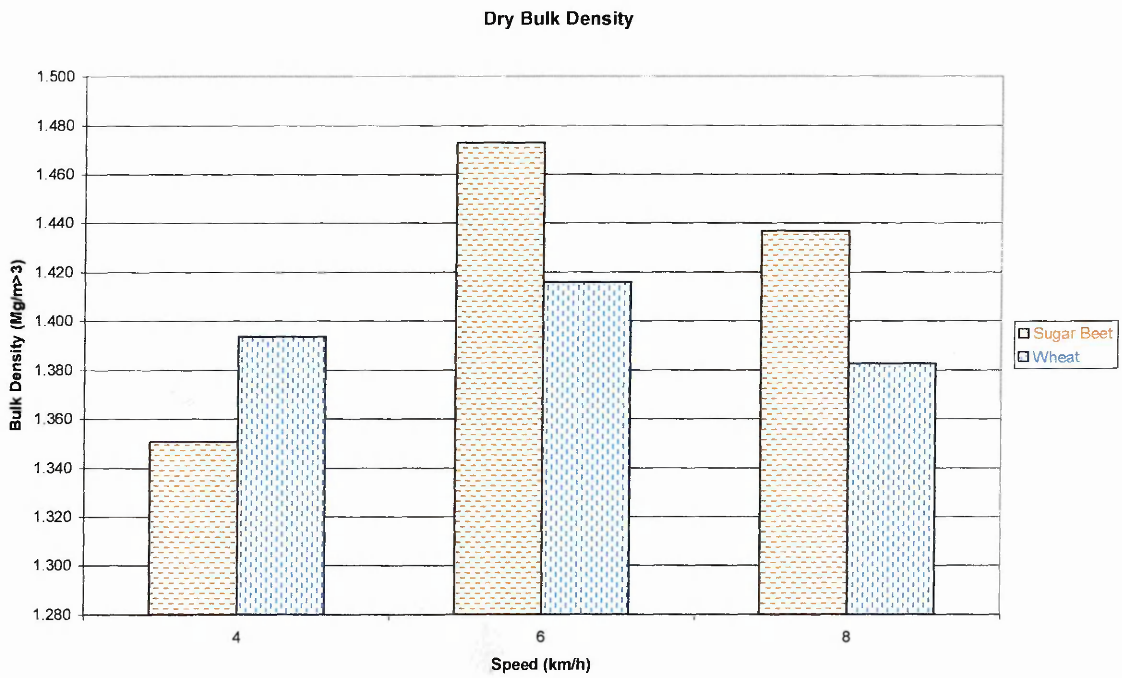

Figure D.4: Soil dry bulk density for seed and speed

D.3. Soil Moisture Content

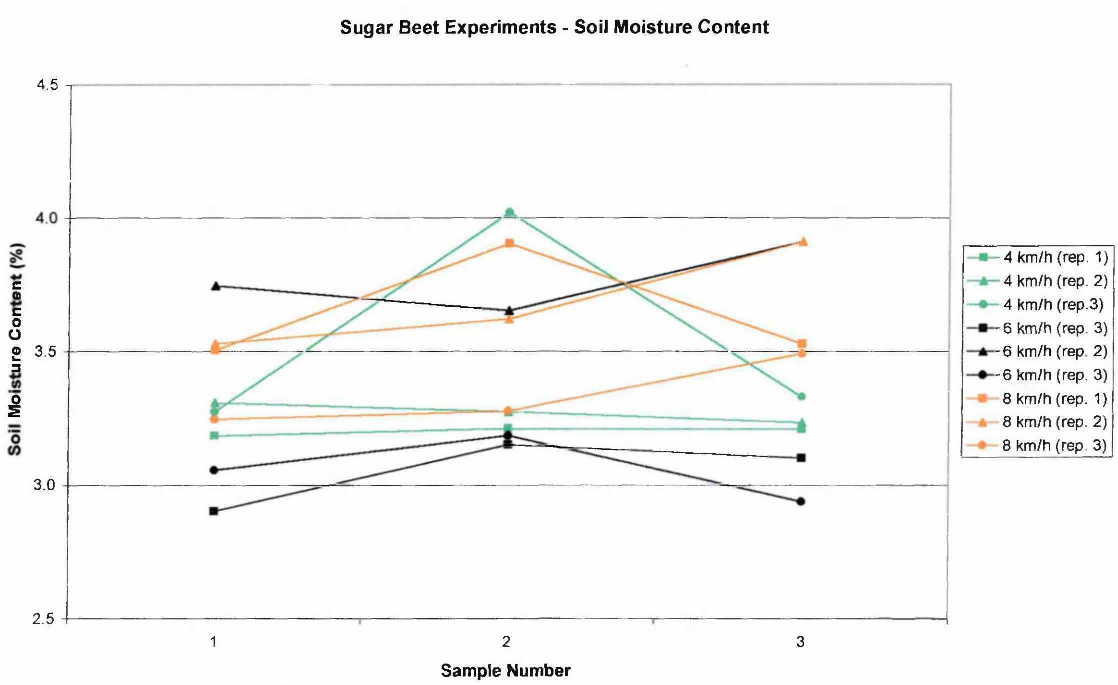

Figure D.5. Soil moisture content for the sugar beet experiments

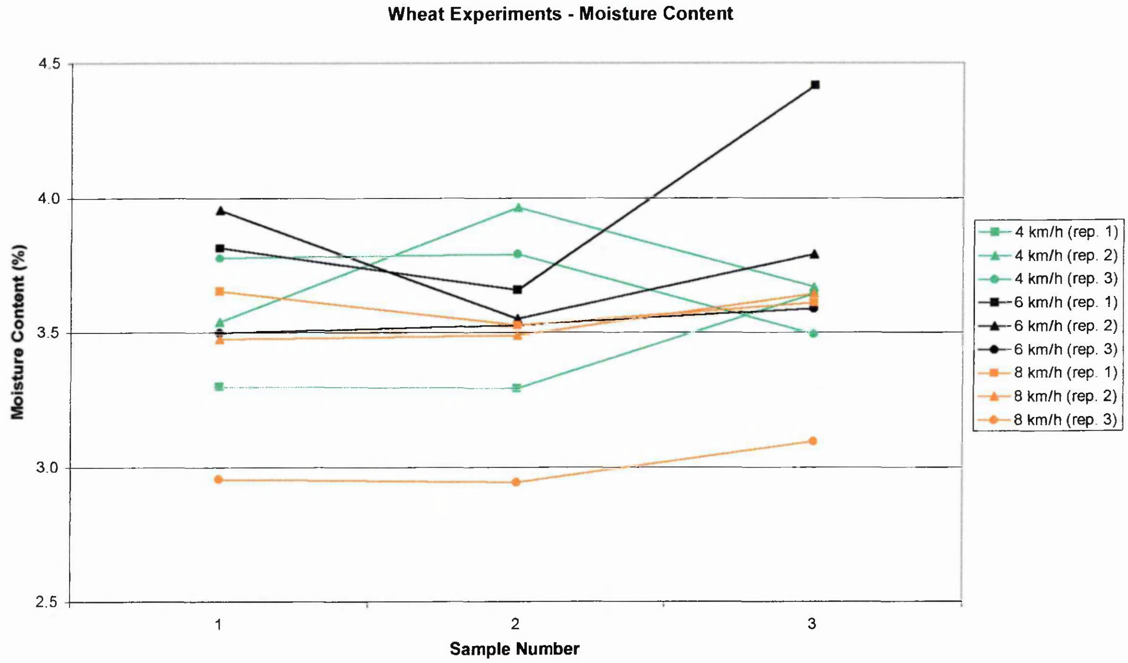

Figure D.6: Soil moisture content for the wheat experiments

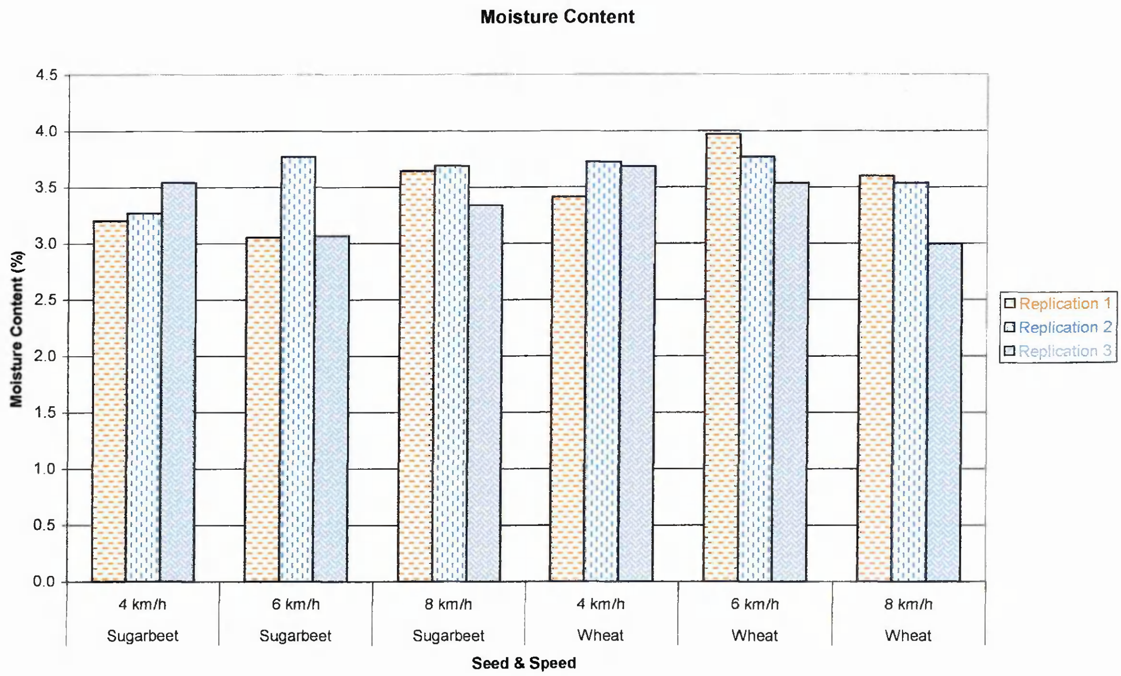

Figure D.7: Soil moisture content for seed, speed and replication

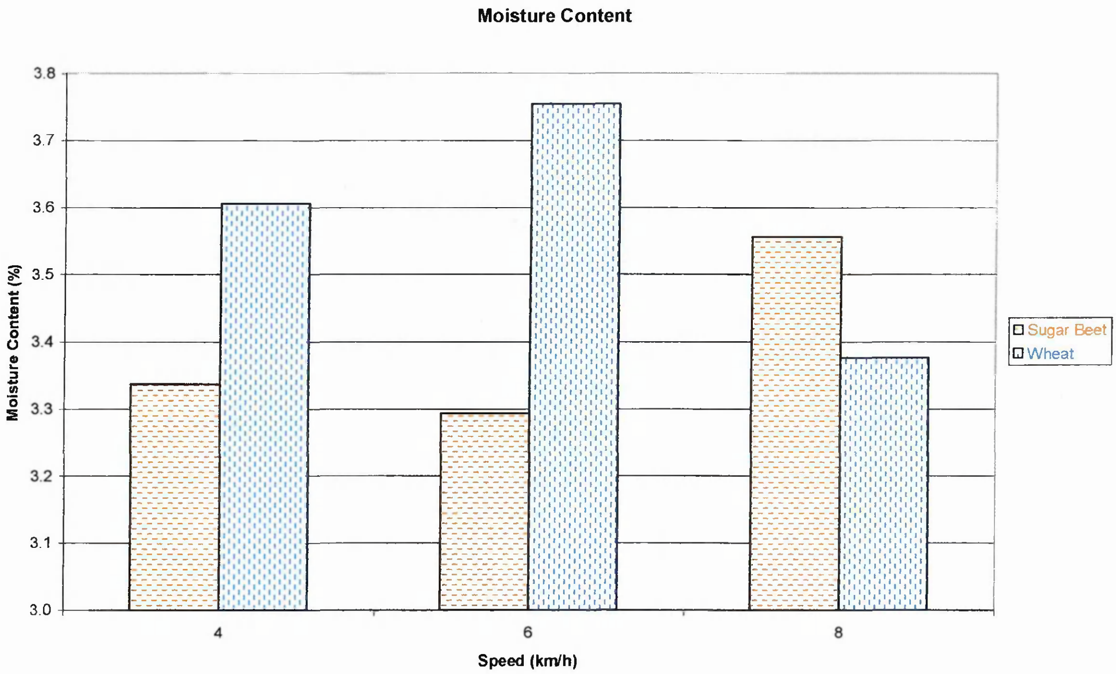

Figure D.8: Soil moisture content for seed and speed