AC 2008-420: EXPERIENCES WITH THE DESIGN AND DEVELOPMENT OF A NOVEL RAPID PRODUCT MANUFACTURING TECHNIQUE IN THE BATCH PRODUCTION OF MINIATURE INDUSTRIAL COMPONENTS.

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Experiences with the Design and Development of a Novel Rapid Product Manufacturing Technique in the Batch Production of Miniature Industrial Components

Abstract

This paper presents a novel rapid product manufacturing technique that will reduce cost and compress time for delivery of products produced in batches. The technique is composed of four stages – digital prototype, computer aided engineering analysis, physical prototype and rapid tooling manufacturing system. The technique effectively integrates the contemporary advanced manufacturing technologies such as solid modeling, CAE, reverse engineering, rapid prototyping and rapid tooling in improving the product design, analysis, prototype, mould and production process. Example of products developed through this technique is also reported in the paper. The initial findings prove the potential of the technique in reducing the time and cost of product development and manufacturing in the quantity or batch production environment. This technique is experimented through the senior design project and proved highly effective in presenting opportunities for students in applying various state of the art product manufacturing technologies that they have learnt in their engineering technology curriculum.

Introduction

Global competitions force manufacturers to constantly innovate new product manufacturing strategies in reducing product development cost and time. For example, Rapid Prototyping can cut new product development costs by up to 70% and the time to market by 90%.[1] There are situations were the customer has requirement for a small quantity, say 25 numbers, of complex product (toy gun for a special game as an example) within a delivery time of 7 days. This type of production requirement falls into the category of batch or quantity production. And, this batch manufacturing of complex parts/product poses special challenge to manufacturers in meeting the target cost and delivery time. None of the contemporary technologies such as traditional manufacturing processes, Computer Numerical Control (CNC) machining or rapid prototyping will offer cost effective solution for this type of manufacturing. To solve this problem, the proposed novel technique of integrating new technologies such as 3D modeling, Computer Aided Engineering (CAE), Rapid Prototyping (RP) and Rapid Tooling (RT) must be considered. These stand alone new technologies have proven record of reducing product manufacturing cost and time. When these technologies are properly integrated the cumulative effect will be the optimum cost and time for batch manufacturing [2]. Details of this rapid product manufacturing technique and the example of products manufactured by this technique are discussed in the subsequent sections.

Design of Integrated Product Manufacturing Technique

Customers demand high quality and reliable products that are cost effective and delivered on time. Contemporary manufacturers have the option of selecting optimum technologies or

processes to suit their manufacturing environment. When these technologies are judiciously combined to address a specific manufacturing challenge such as the one presented in the paper, rapid product development for quantity production, will produce suitable results in terms of cost, quality, and time. Technologies such as Computer Aided Design, Computer Aided Engineering, Rapid Prototyping, and Rapid tooling and manufacturing are combined for this purpose.
When rapid prototyping is adopted to fabricate production tooling the term rapid tool making is used. There are two types of rapid tool making: Indirect and Direct Tooling. In this project, indirect tooling is considered, which consists of using a physical model as the pattern to create a mold that subsequently will serve as a tool for quantity production. This rapid product development system is formed by a set of activities that are being constantly monitored in each stage of the process to ensure the final result that are reliable and appropriate to the requirements established by the customer. Customer feedback is incorporated in the product design and process optimization of various stages of manufacture in ensuring the reliability and quality of the product produced.

As already mentioned, this system consists of four stages: digital prototype, virtual prototype, physical prototype, rapid tooling and manufacturing. The first stage is essentially the design and 3D modeling of the product using a CAD system. This is useful to detect any failure in the design, in which case; parameters and geometry are adjusted for design optimization. One of the advantages of CAD models is that modifications are possible to perform in minutes without incurring more expenses in the later stages of manufacturing.

Once the model is approved, the engineering analysis can be performed on the 3D solid model by treating this as a virtual prototype to establish the optimum manufacturing process parameters[3]. This analysis can be performed using CAE software without having to use the physical prototype. This further saves cost and time on the product development and manufacturing. Making design changes based on the manufacturing process being used to make the product is popularly know as Design for Manufacturing or Concurrent Engineering. Once the design is finalized, the next step is to select a proper rapid prototyping technique to fabricate the prototype of the product.

The popular RP methods that are commercially available include Stereo lithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Manufacturing (FDM), Laminated Object Manufacturing (LOM), Ballistic Particle Manufacturing (BMP), and Three-Dimensional Printing (3-D printing)[4]. In this project, 3-D printing is employed to fabricate the prototype of the product under consideration. Compared to conventional machining methods, rapid prototyping technology significantly reduces time and is therefore more efficient[5]. The process consists of adding layers one over another until the desired shape is achieved. The interface between the CAD program and rapid prototyping machine is achieved by the stereo lithography file format (stl) and most of the CAD programs are equipped to generate stl format from the digital models. Orientation of the component must be ensured before being loaded to the rapid prototyping machine and also the appropriate scale. This process outputs three dimensional physical models directly from the digital data faster and less expensively than any other method.

Once the physical prototype is ready, construction of the production mold begins. This mold should be designed in a way in which the pieces do not become trapped inside. For this reason, it is necessary to analyze the component to be produced in order to determine which type of mold is employed. Casting processes include open or close molds; expendable or permanent[6]. For this project permanent open mold using Room Temperature Vulcanized Urethane (RTVU) is used because it is easier to manage. This means that the moment the material is poured, no further procedure is necessary to degas the solution because it does not trap any air bubbles. In addition, this material is excellent for detail, flexibility, and durability. One of the important properties of Urethane is that it can behave as elastomers, rigid hard thermosets, or injection moldable thermoplastics. An elastomer can be designed to suit a particular application by varying the reacting substances. After the curing time of twenty four hours is completed, components can be cast one by one until the batch size required is completed. This type of mold is compatible with a variety of materials such as resins, wax, epoxy, polyester, urethane, concretes, and plasters with proper release agents which facilitate in releasing the components from the mold. This technique is ideal in addressing the problem of batch production of complex parts that demands short lead time. This is a novel manufacturing technique in the sense that it draws from the advantages of the existing new technologies. Its overall architecture is shown in Figure 1.

Inspection procedures are often performed manually. Sometimes inspection is time consuming with the manufactured parts. Because of the time and cost of manual inspection, statistical sampling procedures are generally used to reduce the need to inspect all the parts[7]. Since the batch associated with this project is small, all of the components are inspected manually for conformance with the design dimensions and tolerances.

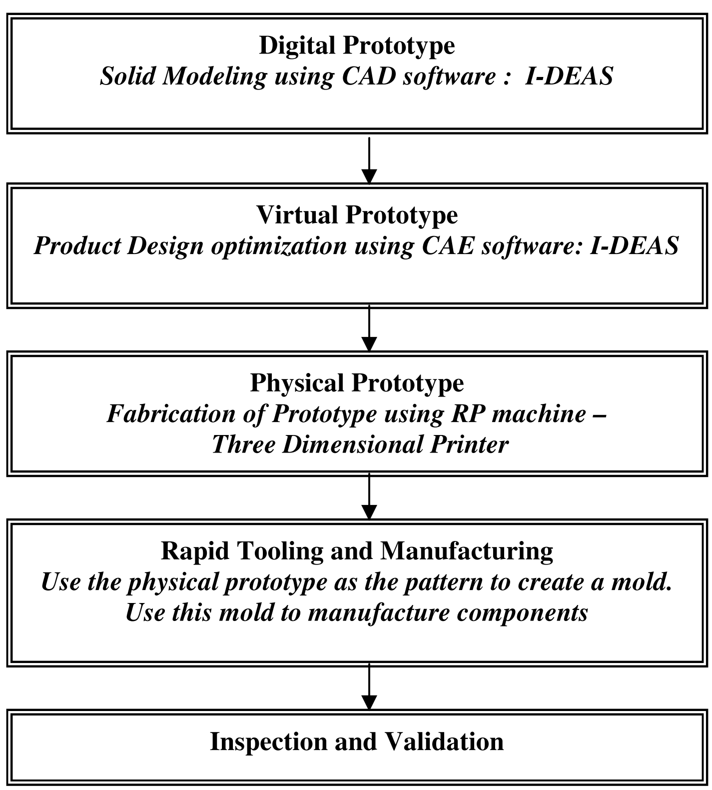

Figure 1: Architecture of the Integrated Product Manufacturing Technique

Application

The rapid product development technique was tested with the fabrication of two types of plastic gears. Each batch has 25 plastic gears. A gear with hub (A) and a simple gear (B) were the components selected for this purpose. The dimensions were established as shown in Table 1. 3D solid models of the gears were created with the gear design parameters using the Integrated Design and Engineering Analysis Software (I-deas). First of all, the tooth profile was designed (Figure 2) and the final design of the gears were arrived as illustrated in Figure 3 and Figure 4. The design of the gears can be optimized by performing engineering analysis using the same software treating the solid models of the gears as the virtual prototypes. The optimized digital prototype was exported as *.stl* file format for further processing.

Table 1: Model Parameters

Gear Parameters	Gear A	Gear B
Teeth	20	27
Pitch Diameter (in)	1.667	2.25
Outside Diameter (in)	1.833	2.417
Pressure Angle (◦)	14.5	20
Bore (in)	0.625	0.625
Face (in)	0.75	0.75
Hub Diameter (in)	1.41	----
Hub Projection (in)	0.50	----
Overall width (in)	1.25	0.75

Physical prototypes of the gears are produced using the popular three-dimensional printer – RP method. This technology is capable of producing the elastomer prototype with a layer thickness of 0.089mm to 0.203mm in less than four hours. Various stages of preparing the Rapid Prototyping machine for the production of the gears which in turn was used in rapid tooling are shown in the Figure 5 and Figure 6. The prototype or the rapid tool produced by this method is accurate. The procedure after releasing it from the 3D printer consists of cleaning the prototype with compressed air in an enclosed chamber to remove the extra material that the machine leaves behind and applying sealant to enhance hardness and durability of the part (Figure 7).

How to choose the best material and process for rapid manufacturing application?

The material and process are chosen to reflect the best blend of the desired cost, quality, material characteristics and timing. The material used to fabricate the mold is room temperature vulcanizing (RTV) urethane which cures without using oven heating. RTV silicone molding is a well-recognized rapid tooling method for producing small quantities of production-like prototypes of plastic molded parts.[3,8] This provides short mold lead times coupled with exceptional detail and surface finish. Complex parts with tough geometries and undercuts can be produced using this process. RTV molding is very cost effective at low quantities while maintaining good accuracy and excellent design detail. The parts produced using this method can be color matched and textured with a variety of material characteristics. The RTV Silicone

Molds are used when the project demands short lead time, low volumes, production-like characteristics, and fine detail and surface finish.

The procedure to do this mold consists of fastening the prototype to the bottom of a container. Since urethane sticks to most objects the gear was soaked with a release agent (Figure 8). The method used to find the volume of the mold consists of filling the container that had the gear with rice, and then putting the rice in a measuring container. Six ounces of material are needed to fabricate this mold. With this information the appropriate quantity of urethane is stirred for two minutes (Figure 9); after that, it is poured in to the container (Figure 10). Once poured, the curing time takes twenty four hours, and the mold is ready to produce the desired two batches of twenty five gears (Figure 11).

In order to simplify the molding process, a user friendly material is selected. In this case, plaster is used to make the final components (two types of gears). The cycle time to construct one gear, from the moment of pouring the plaster in the mold to the moment it is finally released from the mold is thirty minutes (Figure 12, 13 & 14). The required 50 gears were produced successfully and the time taken from the design stage to production is just 10 calendar days (Figure 15). The cost of production of these gears is extremely low (about $50, not including the infrastructure cost). Comparing to the traditional development and manufacturing mode, the gears produced using the integrated manufacturing system can reduce cost by up to 50% and the time-to-market by a whopping 75%. When compared to the context of satisfying urgent requirement of batch product quantities with respect to time, the technique is clearly worth pursuing as demonstrated by the case study presented in this section.

The inspection of the gears was performed using a profile comparator and a Vernier caliper (Figure 16). The results are very accurate since 92% of the parts achieved the required parameters (Table 2 & 3). The other inspection process consisted of verifying the surface finish and finding the surface defects in each of the parts. The produced parts were of acceptable standards within the stipulated tolerance limits. Delivering the batch product quantities starting from the 3D CAD solid modeling to fully functional production gears in less than 10 working days is clearly phenomenal and this technique is likely to get full industrial acceptance and grow in the future.

Delivery time compression for batch production

This Rapid Product Development and manufacturing technique is immensely suitable for batch or quantity manufacturing of complex product designs. In the case of producing batch quantities of plastic gears will necessitate substantial amount of time when produced using CNC gear processing machine or by the injection molding process using dies. This technique judiciously takes the advantages of rapid product prototyping and tooling and then combines with the conventional mass production process such as rubber or plastic hand molding in delivering the product in required batch quantities. The two test batches of gears were produced in an extremely short span of 10 working days. This technique when perfected and employed in industries will further compress time for quantity production. There are a few industries available today that employ this technique that cater to the demand of batch produced complex parts or products[8].

Educational benefits

This project has provided valuable hands-on experiences with the state of the art manufacturing technologies to the senior design students. Manufacturing engineering technology students get exposure to the contemporary manufacturing technologies such as CAD/CAM, CAE, Reverse engineering Rapid prototyping and manufacturing processes. But, seldom have they got to use all of these technologies to address an interesting real-world problem. Project like this provides them with opportunities to apply the advanced manufacturing concepts that they have learnt during the course of the program. The process of integration of these manufacturing technologies provides the students with the real-world manufacturing experience in dealing with the problems in industries. Rapid manufacturing is fast becoming an accepted technological practice to solve the problem posed by batch manufacturing of complex product designs. In the past five years, there are several industries ventured in this field of manufacturing and specialized in the area of Rapid product development and manufacturing. These industries need engineers and technologists who have been trained in this advanced field of manufacturing and product development. Entrepreneurial opportunities in this area of manufacturing are another huge plus for the budding engineers/graduating students in the engineering technology programs. Hence, there is a need to include this emerging manufacturing technique in the mechanical and manufacturing engineering technology curriculum. This technique can be included in one of the existing advanced manufacturing technology courses such as product and process design or as a senior design project. The Applied Engineering Technology department at the University of Texas at Brownsville is planning to include this rapid product manufacturing technique as one of the key laboratory component in the engineering technology curriculum.

Conclusions

In this paper, we have presented a product development and manufacturing technique that integrates the contemporary new manufacturing technologies such as 3D CAD, CAE, Rapid prototyping and Rapid Tooling manufacturing process. This technique draws the advantages of all these manufacturing technologies in reducing the cost and time for product development and manufacturing. Also, this technique addresses specifically the problem of batch manufacturing of complex parts with short lead time; where other contemporary manufacturing processes individually can not address the problem. It is demonstrated that this technique can effectively reduce design and manufacturing cycle time and reduce the development cost, which is an important factor in the world of manufacturing. This project is undertaken as a senior design project and proved immensely beneficial for the graduating manufacturing engineering technology students in gaining real world, hands-on experience in contemporary manufacturing technologies and its integration. This technique when adopted for batch manufacturing or new product development shows a high potential for faster response to market and customer's demands. As a consequence, it will emerge as an important technique in reducing the manufacturing cycle time and minimizing the product development cost in the future.

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8. Web site: http://bastech.com/

Appendix

This appendix includes a set of pictures and images that describes the sequence of the Rapid Product Manufacturing Technique in the batch production of industrial components.

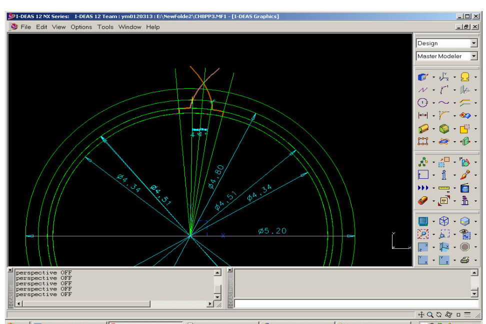

Figure 2: Tooth profile before it is extruded on I-deas.

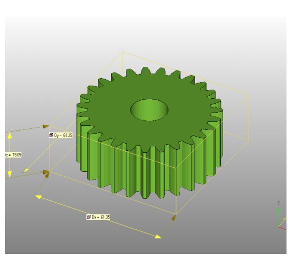

Figure 3: Helical gear.

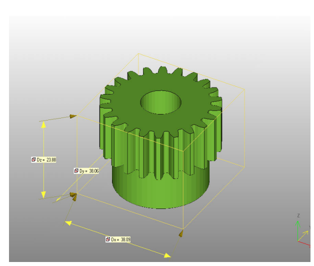

Figure 4: Helical Gear with hub

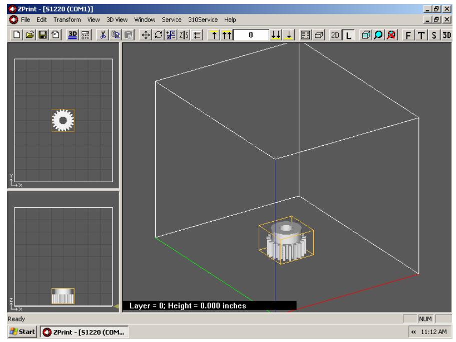

Figure 5: Print screen of the .stl file been properly oriented.

Figure 6: Loading the part using Three-Dimensional Printer

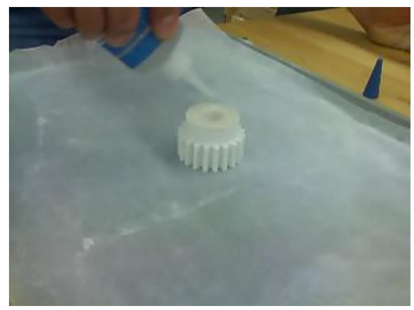

Figure 7: Gluing together the layers.

Figure 8: Applying the release agent to the pattern.

Figure 9: Mixing Urethane material

Figure 10: Pouring the Material

Figure 11: After 24 hours of curing, mold is ready for production.

Figure 12: Plaster preparation

Figure 13: Plaster solidification in the mold.

Figure 14: Component release from the mold.

Figure 15: Batches of gears

Figure 16: Measuring the components with profile comparator and Vernier caliper

Table 2: Gear Parameters obtained using Profile Comparator and Vernier Caliper

PARAMETERS LOG

		Prototype	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Pitch	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Teeth	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Pitch Diameter (in)	1.667	1.67	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Outside Diameter (in)	1.833	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83
Pressure Angle (°)	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Bore (in)	0.625	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Face (in)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Hub Diameter (in)	1.41	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Hub Projection (in)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Overall Length (in)	1.25	1.25	1.25	1.26	1.25	1.22	1.25	1.25	1.25	1.25	1.23	1.24	1.25	1.25	1.21	1.26	1.26	1.24	1.25	1.26	1.25	1.25	1.25	1.26	1.25	1.25	1.24

	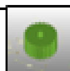	Prototype	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Pitch	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Teeth	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
Pitch Diameter (in)	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
Outside Diameter (in)	2.417	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
Pressure Angle (°)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Bore (in)	0.625	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Face (in)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Hub Diameter (in)	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Hub Projection (in)	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Overall Length (in)	0.75	0.75	0.75	0.75	0.75	0.75	0.74	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.73	0.75	0.75	0.75	0.75	0.75	0.75

Table 3: Gear Parameters obtained using Project Comparator and Vernier Caliper

DATA LOG

Gear Profile

Nominal (Target) ±0.01 at all points.
Fulfill with this condition=2
Do not fulfill=0

	Batch 1			Batch 2			Batch 3			Batch 4			Batch 5			Batch 6			Batch 7			Batch 8			
Runs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Gear A	2	2	2	0	2	2	2	2	2	2	2	0	2	2	2	2	0	2	2	2	2	2	2	2	2

Surface Finish

Requiring hand finish.
Smooth =2
Rough =0

	Batch 1			Batch 2			Batch 3			Batch 4			Batch 5			Batch 6			Batch 7			Batch 8			
Runs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Gear A	2	2	2	0	2	2	2	0	2	2	0	0	2	2	2	2	2	2	2	2	0	2	2	0	2

Defect Count

Evaluate them from 0-5 number of defects.
Zero Deffects =2
One or two deffects =0

	Batch 1			Batch 2			Batch 3			Batch 4			Batch 5			Batch 6			Batch 7			Batch 8			
Runs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Gear A	2	2	2	0	2	2	2	0	2	2	2	0	2	2	2	2	2	2	2	2	0	2	2	2	0

Total Evaluation

	Batch 1			Batch 2			Batch 3			Batch 4			Batch 5			Batch 6			Batch 7			Batch 8			
Runs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Gear A	6	6	6	0	6	6	6	2	6	6	4	0	6	6	6	6	4	6	6	6	2	6	6	4	4

	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6	Batch 7	Batch 8
Mean:	6	4	4.6666667	3.3333333	6	5.3333333	4.6666667	5.3333333