Model-based Inspection for the Control of Quality in Advanced Manufacturing Environments

Shaniel Davrajh and Glen Bright
University of KwaZulu-Natal, Durban, South Africa

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Abstract: Manufacturing processes for markets that involve high levels of customization are inherently exposed to unpredictable and often inconsistent demands. The use of statistical methods for controlling quality in these environments is not suitable. The implementation of 100% inspection would guarantee high levels of quality but involves high inspection costs, whereas 0% inspection is associated with high throughputs without being able to guarantee the outgoing quality of products. This research used the Expected Value Formula to provide a model that determined whether an inspection station should be activated or not. The model-decision depended on specified parameters such as the internal, external and appraisal costs as well as the significance of the inspected feature. The overall profits and Cost of Quality metric were used to analyse the system performance and compare the model-based inspection criteria to the 100% and 0% inspection strategies, using simulations performed in Labview. The model-based inspection showed an overall increase in profits gained for both low and high customer significance ratings with a minimisation of the Cost of Quality, and was therefore considered to be more suitable to manufacturing environments which experienced frequent reconfigurations due to changes in customer requirements.

1 INTRODUCTION

Product markets are becoming highly unpredictable, specialised and more difficult for manufacturers to satisfy (Nambiar, 2009). The unpredictable nature of changes in customer requirements necessitates a response in product and process design that is able to encapsulate these changes. At the forefront of the competitive advantages that a manufacturer must strive to achieve, is the ability to satisfy a customer (Pollard et al., 2008). Manufacturers must then focus on issues pertaining to quality. According to Goetsch and Davis (2010), quality should not be considered as a fixed metric, but instead should timeously change according to customer requirements. Advanced manufacturing environments which implement high levels of customer design must consider the effect of quality repercussions on overall profit in a highly competitive market. Current systems are unable to match the future quality demands that will be placed on manufacturers.

The manufacturing strategies of Reconfigurable Manufacturing Systems (Koren et al., 1999) and Mass Customisation (Da Silviera et al., 2001) converge onto the common goal of providing high levels of customisation through production of a variety of parts within a defined family. These parts are intended to be configured within boundaries specified by the manufacturer and use reconfigurable equipment to accommodate changes in customer requirements. Research into the implementation of reconfigurable inspection equipment is still on-going and rare mention of the implementation of this inspection equipment has been made. The strategy of performing 100% inspection using processes with high reliabilities is certain to ensure that high levels of quality are delivered to the customer. The disadvantage of this inspection strategy is that it negatively impacts on the profits associated with the manufacture of a product by increasing manufacturing times and costs. 0% inspection leads to the admittance of defective products throughout the line and will lead to an increase in unsatisfied customers as well as loss in profits due to compensatory costs.

The research presented in this paper addresses a solution to the implementation of reconfigurable inspection equipment, and forms part of a holistic solution to the management of quality within an

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Advanced Manufacturing Environment. The consideration of a product as a set of features allowed for a user to specify the features that were of most interest to them. The layout of the inspection equipment was based on the classification of significant features. A model that incorporated the customer-rated significant features as well as process non-conformance rates was then developed using the Expected Value Formula (statlect, 2013). This model was used to determine when to perform inspection at a given inspection station. The sanctioning of customers to choose the features of a product that were personally significant allowed for the maintaining of the dynamism in the quality delivered to the customer. Labview (www.ni.com/labview) was used to simulate the model and quantify and compare the overall profits and Cost of Quality (CoQ) metric (ASQ, 2013) of the model-based inspection, 100% inspection and 0% inspection strategies. The results indicated that the model-based inspection strategy was better suited to environments in which the significance of product features varied than the other two inspection strategies.

2 QUALITY COSTS

It is imperative to maintain high levels of product quality within a manufacturing environment; however the process of quality control does not necessarily change a product and hence does not directly increase the value of the profit gained. Quality management is considered to have the dual objectives of maximizing the quality of conformance and minimizing the associated costs. The CoQ approach renders a single metric in reconciling these two conflicting objectives and therefore allows for a single metric to be optimized whilst accommodating a wide range of individual customer needs. According to Zaklouta (2011), no single definition of CoQ and its constituent elements exists. Juran (1951) considered CoQ as all the costs that would disappear if every process in the lifecycle of a product had a non-conformance rate of zero. Crosby (1979) introduced the division of quality costs into conformance and non-conformance costs. The Prevention-Appraisal-Failure (PAF) model was the most commonly accepted CoQ model since its adoption, as discussed by Zaklouta (2011). Prevention costs refer to the costs involved with the reduction in frequency of non-conforming products. Such costs include supplier audits, process adjustment, calibration and maintenance, and can be held constant in a defined manufacturing environment according to (Zaklouta, 2011). Appraisal costs are the costs associated with the detection of the non-conformance of a product. Inspection and testing are the two types of appraisal costs. Failure costs are divided into the costs associated with internal failures and external failures respectively. Scrapping and reworking fall under internal failures whilst complaint adjustment and product recalls are external failure costs. The basic Lundvall-Juran curve, shown in Figure 1 was represented by Foster (1996) and depicted the Economic Quality Level (EQL). This level is depicted by the point at which the cost of quality is a minimum and hence provides a numerical goal that should be achieved for a given system. The graph indicates that the Appraisal and prevention costs (C1) increase, whilst failure costs (C2) decrease, as quality levels increase. The total quality costs are determined by the summation of C1 and C2.

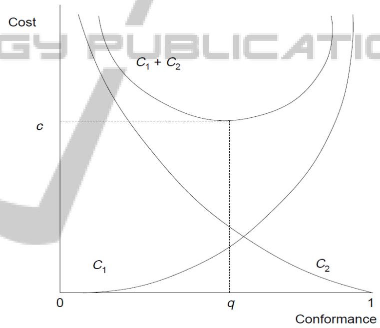

Figure 1: Lundvall-Juran curve (Foster, 1996).

The EQL approach was criticised by Crosby (1979) as it implied the acceptance of defective parts reaching the customer. This research was based on satisfying the quality requirements of customers as well as minimizing the costs associated with inspection. The possibility of defective products reaching customers through non-inspection was considered acceptable, if and only if it was financially feasible.

3 DEVELOPMENT OF THE INSPECTION MODEL

A product family, as described in (Tseng and Du, 1998), was considered to be a set of components wherein each component contributed both individually and holistically to the functionality of a product. This research considered a product as a set of features which were governed by the selection of components from the product family. The configuration of a product entailed the customer selecting the modules of choice and then specifying the values of the features associated with the selected modules within the specified boundaries. The customer was required to enter the significance of the selected modules through specification of a product rating and Significance Factor (SF), which were used to determine the external costs associated with failure of the product or component. The product rating was defined as the rating that described the consequences of failure of the product whilst in use and would be determined by the manufacturer. An assembly line with parallel lines feeding into the assembly stations was considered for the manufacturing of a completed product configuration. The parallel lines represented the feeding in of outsourced modules or performing in-house fabrication of the relevant modules. The locating of inspection stations throughout the manufacturing lifecycle of a product has been described in (Davrajh and Bright, 2012).

There were two options following a manufacturing process namely inspection and non-inspection from which the following possibilities arose:

- Inspect a good part
- Don't inspect a good part
- Inspect a defective part
- Don't inspect a defective part

The selling price (Sell) of the product was assumed to be determined through market related research. The external failure cost was determined using equation (1)

$$C_{ext} = \Pr oduct\_rating * \frac{SF}{\sum SF} * Sell \qquad (1)$$

The cost of manufacture (C_m) was considered as the sum of all the manufacturing costs associated with the product. C_i was defined as the inspection costs associated. The stochastic nature of manufacturing systems forced the introduction of probabilities with respect to the reliability of the manufacturing and inspection processes. The probability of a conforming product feature after going through a process was modelled as the product of the reliabilities of the current process and the processes before it. The conformance rate of the inspection process was also considered in this model. Figure 2 shows the possible paths and profits that a product may follow after a process. These profits were quantified with respect to the formulae associated with each path and are presented in Table 1.

Table 1: Tabulated profits for inspection and non-inspection of defective and acceptable parts.

Profit Variable	Description	Formulae
PR_{IG}	Inspection of an acceptable product	Sell – (Cm+ Ci)
PR_{ID}	Inspection of a defective product	– (Cm+ Ci)
PR_{DIG}	Non-inspection of an acceptable product	Sell – Cm
PR_{DID}	Non-inspection of a defective product	Sell – (Cm+Cext)

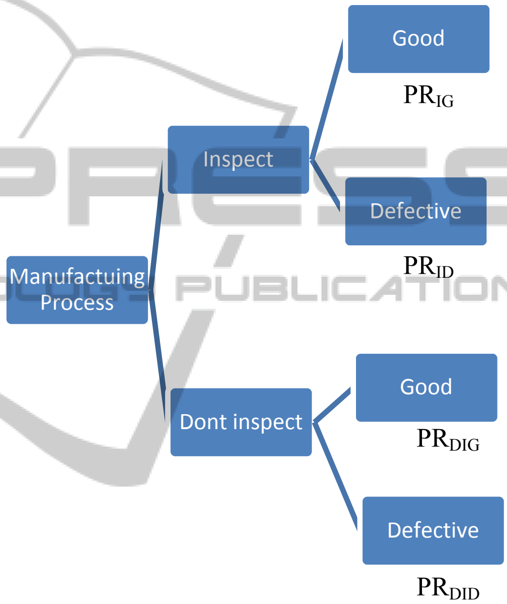

Figure 2: Layout of possible Profits following a process

Wherein:

For the path involving inspection, the profit was considered as a discrete random variable Xi, having support $R_{xi}=\{PR_{IG},PR_{ID}\}$ and a probability mass function $P_{xi}(x)$ as shown below:

$$P(Xi = xi) = \begin{Bmatrix} p & : xi = PR_{IG} \\ 1-p & : xi = PR_{ID} \\ 0 & : otherwise \end{Bmatrix}$$

Considering the case of non-inspection, the profit was modelled as a discrete random variable Xdi with support $R_{xdi} = \{PR_{DIG},PR_{DID}\}$ and a probability mass function P_{xdi} presented as:

$$P(Xdi = xdi) = \begin{Bmatrix} p & : xdi = PR_{DIG} \\ 1-p & : xdi = PR_{DID} \\ 0 & : otherwise \end{Bmatrix}$$

The expected value for each case was represented by equations (2) and (3) respectively:

$$E[Xi] = \sum_{xi\varepsilon R_{xi}} xi * P(xi) = p * PR_{IG} + (1-p)PR_{ID} \quad (2)$$

$$E[Xdi] = \sum_{xdi\varepsilon R_{xdi}} xdi * P(xdi) = p * PR_{DIG} + (1-p)PR_{DID} \quad (3)$$

The decision to inspect was then executed when the following condition was satisfied

$$\frac{E[Xi]}{E[Xdi]} \geq 1$$

The value of p was determined using the reliabilities of the manufacturing processes. The initial reliabilities as specified by the operator were considered for the first run. Thereafter they were updated based on the volume of products produced. Figure 3 illustrates the process flow. For example, if a reliability was 99% that meant that 99 out of 100 were successful. If one more passed through it and was successful, it would have a reliability of 100 out of 101.

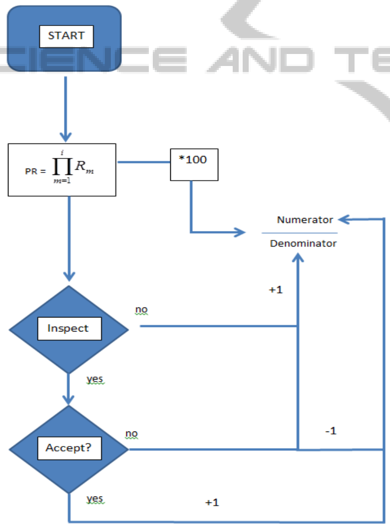

Figure 3: Flowchart describing the updating of the probabilities of the inspection criteria

Assuming that the prevention costs are constant, the quality costs associated with the three different appraisal and failure costs were determined as follows:

$$COQ_{100\%} = \text{Appraisal} + \text{Internal Failure} \quad (4)$$

$$COQ_{0\%} = \text{External failure} \quad (5)$$

$$COQ_{model} = \text{Appraisal} + \text{internal failure} + \text{external failure} \quad (6)$$

4 SIMULATION RESULTS AND DISCUSSION

Figure 4 illustrates the manufacturing layout that was simulated in Labview to compare the model-based inspection criteria to 100% inspection and 0% inspection frequencies. This layout depicted any manufacturing process that was considered significant in the product manufacturing cycle, as discussed previously, with the possibility of an inspection station following the process. The simulation was based on the inspection of a single feature passing through the station.

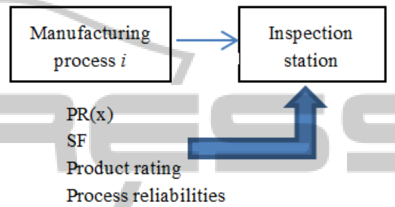

Figure 4: Simulated inspection station layout.

The manufacturing and inspection process reliabilities were assumed to be constant whilst the batch sizes, supplier reliability, processing costs, product rating and SF were varied. The external failure costs were modelled using equation 2 which depended on the replacement costs to the customer. The value of SF divided by the total sum of SFs was used to determine the relative significance of the feature in the context of the entire part. For this simulation, this factor was considered to be 1. The reason for this was that only a single feature inspection was performed. This factor would change when considering more features. Table 2 lists the categorisation of the product rating and its influence on the external failure costs. The use of two values in the same category accounted for the upper and lower extremes of relevant categories.

The inspection simulation interface and numerical results are shown in Figure A1, in the appendix. Twenty trials were performed; however the results of only nineteen tests were plotted for scaling reasons. The supplier rating was varied between 0.7 and 0.95 to simulate the differences in the reliability chain that would occur when producing batches of custom products that would require changes in process configurations. These supplier ratings were inputs to the discrete random generator using the Bernoulli probability function to generate acceptable or defective parts randomly. The tabulated results of the simulations are placed in the

Table 2: Product rating list.

Product rating	Description
1- 2	Low: These values indicate that the failure of the product of component produced has little repercussions and can be accommodate by the replacement of a defective component/product. A customised cellular phone cover would be a typical product with this rating
3- 4	Moderate: Used when failure of the component/product is significant but not critical. The incorrect spelling of a customers' name on a product label is an example of this rating
5-6	Critical: Failure of a product with this type of rating could lead to serious injury of a person. A brake pad is an example of such a product.

Appendix (Table A). Figure 5 (a) illustrates the overall profits of all three inspection strategies displayed on the same axes (y-axis being profit and x-axis being trial number). The results indicated that the model based inspection behaved similar to the 0% inspection strategy for low product ratings and significant feature values. The response of the model-based inspection converged onto the behaviour of the 100% inspection strategy for higher product ratings and significant feature values. The greatest difference between the results of the model and 0% inspection strategies occurred when the product was rated moderate or critical (3-6). The greatest difference between the model and 100% inspection was seen when the product rating was low. The SF directly affects the external costs but due to there being only one feature, this factor did not influence the overall inspection operation as seen in Figures 5 (b) and (c). Negative profits were recorded in some trials. These negative values were a result of the combination of supplier and process reliabilities, along with the product rating and production costs.

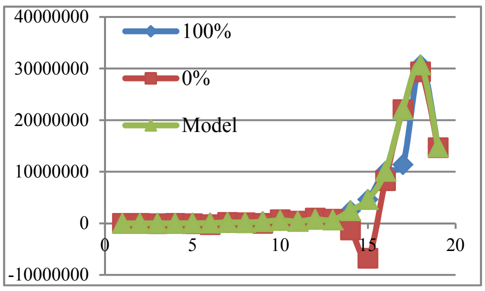

Figure 5(a): Plot of the profits for the three inspection strategies vs the inspection trial number.

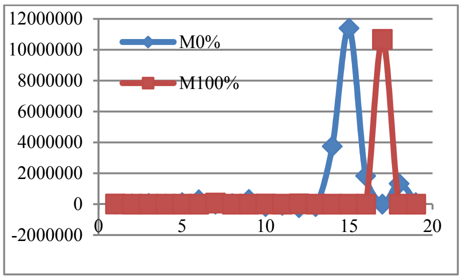

Figure 5(b): Differences in profit between the Model-based inspection and the 0% and 100% strategies.

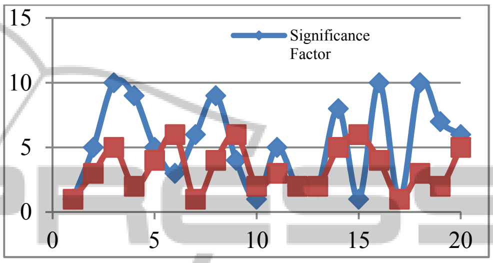

Figure 5(c): Corresponding product rating and SF values for the trials.

The cumulative profits for the 19 trials were plotted, shown in Figure 6(a) to determine the overall difference in performance of the inspection strategies. The plot shows that all the inspection strategies had the potential for profit with the 0% inspection strategy being the most prone to loss in profits for products rated moderate or critical. The model responded like the other two inspection strategies at their optimum when the conditions dictated. This allowed for the model based inspection strategy to have the highest overall profits consistently. Figure 6(b) shows that the overall profits obtained by the model-based inspection were approximately 14% higher than the 100% inspection strategy and 27% higher than the 0% inspection strategy.

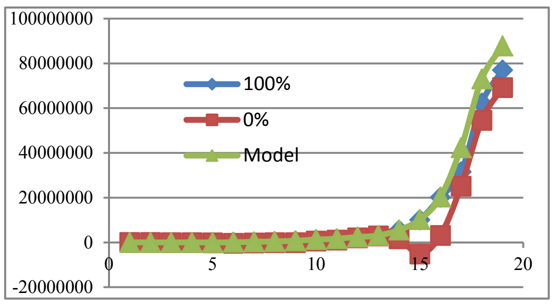

Figure 6(a): Plot of the cumulative profits of each type of inspection strategy.

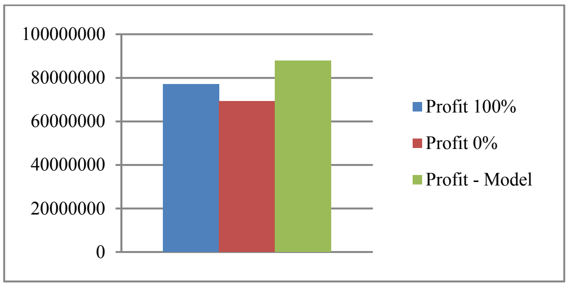

Figure 6(b): Comparison of the total profits for the trials.

The COQ results for each type of inspection were plotted using the results from Table 2. Six simulations were performed with the only variable being the product rating. The relative product rating was divided by the maximum product rating (to quantify conformance quality) and was then plotted against the quality costs associated with each type of inspection (preventative costs being kept constant for each inspection type). Figure 7(a) shows a fluctuation in the cost of quality for the 100% inspection strategy. The appraisal costs for this strategy were constant for the simulation, hence the only factor influencing the plot were the internal failure costs. These internal failures were based on the random values generated during the simulation and the graph shows a relatively low difference between the maximum and minimum costs as expected. Figure 7(b) indicates an increasing cost due to the external failure costs increasing in accordance with the product rating and equation. A larger product rating significantly increases the external failure costs and hence quality costs associated with this inspection strategy. Figure 7(c) show the results of the COQ associated with the model-based simulation. The model was seen to have a minimum COQ when the product rating was low and a stabilisation onto a single cost as the product rating increased. The increase in product rating would have increased the external failure costs and forced an increase in inspection frequency. The only factor influencing this COQ at moderate and critical product ratings were the internal failure costs. Figure 7(d) illustrates the differences in COQ of all three inspection strategies. It can be seen that the model based inspection strategy always maintains a low COQ which is required for minimizing associated production costs and maximising outgoing quality levels in accordance with the customer requirements.

Table 3: Cost of quality values.

Quality of conformance		100%	0%	Model
1	17%	190000	100000	100000
2	33%	190400	202000	190750
3	50%	194800	336000	194800
4	67%	188000	380000	188000
5	83%	192800	535000	192800
6	100%	191200	618000	191200

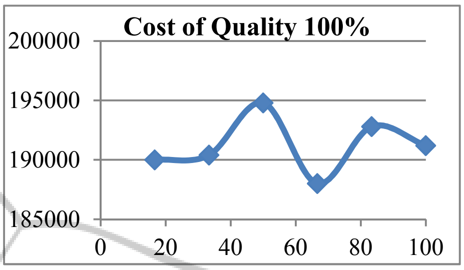

Figure 7(a): Plot of the costs associated with the relative product ratings for the 100% inspection strategy.

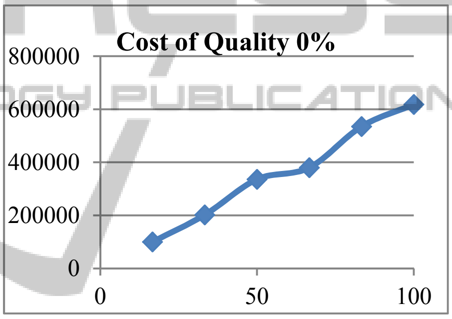

Figure 7(b): Plot of the costs associated with the relative product ratings for the 0% inspection strategy.

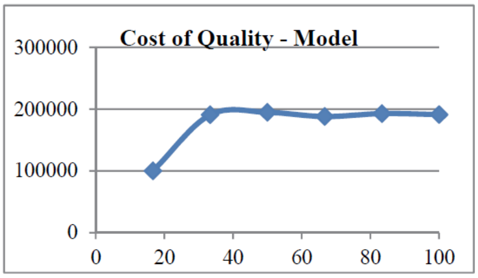

Figure 7(c): Plot of the costs associated with the relative product ratings for the model-based inspection strategy.

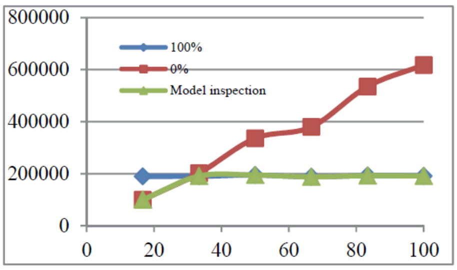

Figure 7(d): Comparison of the costs of quality plotted on the same set of axes.

The twentieth trial involved a batch size of 100 000. Due to the high product rating, the difference in profit between the 100% and 0% inspection strategies was extreme. The model was however able to obtain the same profit a with the 100 % inspection.

5 CONCLUSIONS

Advanced manufacturing environments involve frequent changes in product design and process configuration in accordance with changes in customer requirements. The supply chain for such an environment would also have to be dynamic to accommodate these changes. A model to determine the frequency of inspection at a strategically located inspection station was developed using the expected value formula. The inspection criteria considered were the costs associated with the product, the significance of the product to the customer as well as the supplier and process reliabilities. Twenty trials were performed whilst varying the inspection criteria parameters to obtain an overall average performance of the system. The results from the simulation were compared to results of simulations performed to quantify the performance of 100% and 0% inspection process strategies. The 0% inspection strategy was best suited to processes involving high reliabilities and low customer significance ratings. The 100% inspection strategy was best suited to high customer significance ratings. The model-based inspection showed an overall increase in profits gained, for both low and high customer significance ratings, with a minimisation of the COQ and was therefore considered to be more suitable to manufacturing environments which experienced frequent reconfigurations due to changes in customer requirements. Further research into reconfigurable manufacturing systems is currently being performed globally. A fully functional manufacturing environment is currently being implemented at the University of KwaZulu-Natal manufacturing laboratory. On completion, further results will be generated and obtained for simulation of industrial applications.

REFERENCES

Crosby, P. B., *Quality is Free*. 1979, New York, N. Y.: McGraw-Hill.

Da Silveira, G., Borenstein, D., & Fogliatto, F. S., 2001. *Mass customization: Literature review and research directions*, International Journal of Production Economics, 72, (1).

Davrajh, S., Bright, G., 2012. *Implementation of Commercial Products for Reconfigurable Quality Inspection, M2VIP, NZ*

Foster, S. T., 1996 *An examination of the relationship between conformance and quality-related costs*, International Journal of Quality & Reliability Management, Vol. 13 Iss: 4, pp.50 - 63

Goetsch, D. L., Davis, S. B., 2010. *Quality Management for Organizational Excellence: Introduction to Total Quality*, Pearson, N. J.

ASQ, http://asq.org/learn-about-quality/cost-of-quality/overview/overview.html, 2013

http://www.statlect.com/expval1.htm, 2013

Juran, J. M., 1951. *Quality Control Handbook*. 1st ed., New York, NY: McGraw-Hill.

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., and Van Brussel, H.: 'Reconfigurable Manufacturing Systems', CIRP Annals - Manufacturing Technology, 1999, 48, (2), pp. 527-540

Nambiar, A. N.: 'Mass customization : where do we go from here?',World Congress on Engineering , WCE 2009, 2009, pp. 687

Pollard, D., Chuo, S., Lee, B., 2008. *Strategies For Mass Customization*, In Journal of Business & Economics Research, 6, (7)

Tseng, M. M., and Du, X., 1998. *Design by Customers for Mass Customization Product*, CIRP Annals - Manufacturing Technology, 47, (1), pp. 103-106

www.ni.com/labview, 2013

Zaklouta, H., 2011. *Cost of quality tradeoffs in manufacturing process and inspection strategy selection,*MSc Thesis, MIT

APPENDIX

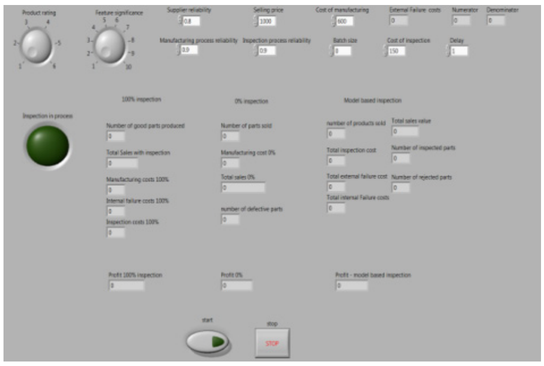

Figure A1: GUI for the inspection simulation.

Table A: Tabulated results from the inspection trials.

Trial number	Batch size	Selling price	Ci	Cm	Product rating	SF	Supplier	Manufacturing	Inspection	100%	0%	Model
1	10	1000	150	400	1	1	0.7	0.9	0.9	-5300	6000	6000
2	10	2000	300	800	3	5	0.7	0.9	0.9	-2200	-12000	-2200
3	10	3000	450	1200	5	10	0.7	0.9	0.9	-7500	-57000	-7500
4	100	1000	150	400	2	9	0.8	0.9	0.9	10000	10000	10150
5	100	2000	300	800	4	5	0.8	0.9	0.9	22800	-72000	22800
6	100	3000	450	1200	6	3	0.8	0.9	0.9	34200	-252000	34200
7	100	4000	600	1600	1	6	0.9	0.9	0.9	124000	200000	200000
8	500	1000	150	400	4	9	0.9	0.9	0.9	163400	124000	163400
9	500	2000	300	800	6	4	0.9	0.9	0.9	312800	12000	312800
10	500	3000	450	1200	2	1	0.95	0.9	0.9	540600	708000	555450
11	1000	1000	150	400	3	5	0.95	0.9	0.9	375800	441000	376750
12	1000	2000	300	800	2	2	0.95	0.9	0.9	765600	1010000	789600
13	1000	3000	450	1200	2	2	0.85	0.9	0.9	661200	816000	661650
14	10000	1000	150	400	5	8	0.85	0.9	0.9	2460200	-1285000	2460200
15	10000	2000	300	800	6	1	0.85	0.9	0.9	4620800	-6768000	4620800
16	10000	3000	450	1200	4	10	0.92	0.9	0.9	10093800	8268000	10093800
17	50000	1000	150	400	1	1	0.84	0.9	0.9	11389600	22064000	22064000
18	50000	2000	300	800	3	10	0.9	0.9	0.9	30711600	29382000	30711600
19	50000	3000	450	1200	2	7	0.75	0.9	0.9	14760600	14658000	14759300
20	100000	1000	150	400	5	6	0.9	0.9	0.9	30854400	9480000	30854400