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SIMULATION 2002; 78; 330

DOI: 10.1177/0037549702078005562

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A Simulation-based Method for the Process to Allow Continuous Tracking of Quality, Cost, and Time

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A simulation-based methodology is developed for continuously tracking and analyzing the quality of product, associated cost, and time during the manufacturing process. In particular, the metal-to-metal bonding process related to the prefit stage is selected for the study, in which required mating conditions for detail parts that make up the bonded assembly are critical. Finally, the results of the model allow the optimal condition to the supply-chain network and identification of problems that affect the quality and productivity of manufactured goods in a factory on a continuous basis.

Keywords: Tracking quality, simulation, manufacturing process, quality in metal-to-metal bonding process, prefit stage

1. Introduction

This research is aimed at developing a model for continuous tracking of product and process quality, cost, and time during manufacturing. The general objective is to create an analytical approach, which allows identification of problems that affect the quality and productivity of manufactured goods in a factory on a continuous basis. This work is useful for the assembly part, in which dimensional accuracy and measurement are important for the quality. Specifically, for the type of assembly in which the assembly phase gaps are built based on each individual dimension, some of these gaps are not easy to see. Once the major step is finished (final inspection is done), if defects are found, then it is difficult to adjust these gaps. The project is directed to a specific manufacturing process of metal-to-metal adhesive bonding, which is used to fabricate complex lightweight structural aircraft components (assembly part) at an aerospace company.

It is a well-known fact that simulation is an important part of a supply-chain network for forecasting and estimation. The developed simulation model will provide the

following to the company logistics:

- improve the likelihood of obtaining quality parts the first time, in which dimensional accuracy is the focus;
- reduce the chance of having defective parts in the work in process once the defects are identified;
- identify how the various defects can be caught at various stages;
- fix these defects and determine how much it will cost (money and time) the company;
- determine how much it will cost the company to meet the customer's requirements or to achieve a required quality level;
- analyze and identify various optimal scenarios.

As well as the above, the developed model provides the answers related to what happens if the problem is not caught (e.g., whether defects can be reduced by workers' involvement). The present paper develops a general model of the manufacturing process and forms the initial part of the research concerned with tracking quality, cost, and time spent on each manufacturing process.

2. Background and Scope

Adhesively bonded lightweight structural metal parts were traditionally used in military aircraft. However, there has been tremendous growth in the past two decades in the

usage of such parts in commercial aircraft to reduce aircraft weight and consequently improve fuel efficiency. The typical problems faced by industries in this area are as follows:

- The time to develop the manufacturing process for every distinct part takes several months.
- Even after the process has been developed, in general, more than 30% of all parts produced can be subject to expensive nonconformance, resulting in rework and potential scrap.
- The nonconformances are often not found until after the assembly is complete, and sometimes the cause(s) of the problem is never identified. This results either in expensive repairs/rework or part scrapping, affecting the gross margins.

Furthermore, different customers often have different process requirements to produce the same type of finished part. The entire process sequence, though simple, is very unforgiving and therefore requires stringent process control during each and every process stage. Each processing stage is associated with a number of complex, interrelated, and often not easily understood variables. Therefore, slight operator negligence or lack of control at any process stage usually results in defects in the finished cured part.

Due to the above reasons, the scope of this research is to analyze and track product quality at any time and at any processing stage, as well as develop a method for systematic generation and evaluation of alternatives. The analysis is expected to allow qualitative/semiquantitative predictions from three perspectives—quality, cost, and time—thereby providing a sharp focus on the engineering aspect of measuring product quality.

The developed model incorporates qualitative reasoning concepts from experts' technical knowledge. It is expected that the methodology developed would have general applicability to any complex assembly manufacturing system in which tracking of continuous product/process quality is required to improve the bottom line.

3. Literature Review

Most of the research on metal-polymer (adhesive) bonded and other composite structures has so far focused on understanding the individual aspects of various processes involved in their fabrication and how these help in improving the quality of bonded parts [1, 2]. The effort in defining and modeling the quality aspects of production processes from a systems perspective is limited.

However, surveys in the area of manufacturing systems show a rather complete lack of attention when cognizance is given to quality, cost, and time in manufacturing all at the same time. A few studies have combined more than one area at a time—for example, quality and cost [3], cost and time to market [4], quality and inspection planning, and cost, time, and performance [5].

Surveys have revealed that numerous approaches to quality control or quality in manufacturing have been developed over the years. All these approaches are valuable in process selection but fail to take into account the product quality generated by the manufacturing system. The basic elements in a production system such as receiving inspection of incoming materials, quality of detail parts and assembly fabrication, and testing and rework quality play an important role in ascertaining quality. The interrelationships between the elements have a significant effect on the product quality; therefore, understanding of their effects becomes necessary. In many situations, even if all the individual processes involved in the manufacture of a product are performing satisfactorily, it does not necessarily mean that the overall quality of the product will be good. If the product is complex enough, as are metal-bonded parts, a small number of defects occurring at each process stage may accumulate and lead to poor overall product quality.

The related literature in manufacturing systems shows that combining more than one area at a time is cumbersome and hard to manage using theoretical or qualitative models. Because of the complexity of industrial problems, mathematical and optimization models and techniques usually have difficulty in representing most industrial and quality problems. Therefore, to approach real industrial problems, researchers have mainly used computer programs or simulation modeling techniques to handle the complexity of the manufacturing world.

Lester, Enrich, and Mottley [6] pointed out that simulation can be used to imitate real-world relations, and the greater the similarity of the simulation variables to actuality, the more useful will be the study. Simulation also allows for the testing and analysis of "what if" scenarios [7]. According to Smith and Platt [8], one of the major advantages of simulation is in animating the process under investigation.

Witness software is selected for the present simulation. In fact, there is a plethora of simulation software packages available on the software market (e.g., GPSS, Sigma, Simfactory, Promodel, Witness, Simul8, etc.). Each of these has associated strengths and weaknesses, depending on the type and the purpose of the problem and the modeling criteria. Hlupic [9] provided an excellent review of various simulation software packages.

This work will allow manufacturing problems, especially those related to part dimensions, to be identified and fixed after the first occurrence, and desired corrective action is then taken to eliminate the problem from the system. The developed model is useful for the complex assembly of parts in which dimensions are critical and govern the quality of the part. One of the main features of this research is human interaction, and it is considered in terms of operators' experience and their decision level, the visibility of the problem, and the defined inspection level. The model also provides objective and consistent results while evaluating quality-related problems.

4. Method: Description and the Framework

In this research, results of our efforts to model the relevant portion of the manufacturing process by simulation will be discussed with a view to developing simple strategies to alleviate the problems associated with the manufacture of the bonded assemblies.

The model will take into consideration the following:

- the as-designed part tolerances and the visibility of the problem (e.g., various types of bonding defects) associated with the as-designed part tolerances,
- costs and times associated with each process element and so forth. The general structure or framework of the model is illustrated in Figure 1.

The model basically consists of three blocks:

Input Block Interface. This provides various input data for the model in the form of Excel files, as well as the applicable rules or functional relationships specifying the decision rules to be used by the operator during the simulation.

The operator makes suitable decisions using applicable rules (functions), which are developed from knowledge bases (e.g., production and inspection requirements, etc.). The functions allow change in attributes, problem recognition, decision, inspection, rework, requirement, and experience. An overview of the types of functions is described as follows:

- The *change in attribute* function(s) maintains the quality characteristics of the manufactured part and generates a map of the manufacturing process along with the attributes, workstations, sequence of tasks, and cycle time. The map contains information on which attributes are used at what workstation and their sequences, thus allowing one to keep track of the quality of the part.
- The *recognition* function is available for the operator. This function allows one to model the capability of the operator to recognize problems (defects) in the part during manufacturing.
- The *inspection* function is called on to generate inspection criteria for the operator based on the type of part, attribute of the part, and experience level of the operator. In essence, the inspection function represents the eyes of the operator. Again, how far the operator is able to see depends on the defined likelihood function for the experience level of the operator.
- The *decision* functions are used to incorporate the visibility of defects and to tell the operator to perform the inspection. It also works as an on-off (1,0) switch.
- The *experience* function is used to call operators with a specific experience level to perform the work based on their availability. The experience function consists of the defined type of operator experience levels and the likelihood of their ability to detect the problem.
- The *rework/scrap* function directly influences the part's attributes. This function is used to affect the quality of the part at the workstation and finally determines product conformance attributes.

- The *requirement* object is used to bind primary variables together. This is one of the vehicles used to establish the customer's requirement profile for the final part, as well as a means to distinguish primary variables from the dependent variables at each workstation.

It is important to note that the use of these or any other additional functions depends on the type of part, process, and experience level of the operator(s). For example, the possibility of the rework/scrap function to be called on depends on not only the incoming attribute of the part but also the customer's requirements and the experience level of the operator. Thus, rework/scrap generation is a function of the type of inspection being performed, the operator's process environment (workstation, task, and cycle time), the operator's ability to perform the work, and the incoming part type and its attributes on which the operator has little or no control.

Action or Simulation Block. The general scheme or flowchart of events during the simulation is given in Figure 2. The process is represented by the workstations, tasks, and cycle time. The action machine (simulator) is used to advance the simulation clock, keep track of the state of the process, and invoke the ordered movement of the operator and the process.

Output Block. Output block stores the results of simulation. The purpose of the output block is (1) to display the summary of results as the simulation runs, (2) to debug the model, and (3) to analyze the results for future recommendations. Creating a new function or providing appropriate commands to the existing function can handle display of the results. Output files, like the input files, are Excel files.

5. Results

The modeling starts by defining the elements of the model. These elements are machines, buffers, parts, variables, attributes, functions and files, and so on. Depending on the objective of the problem and the limitation of the software package, various elements can be defined.

A specific metal-bonded part, the main landing gear door (MLG door), is selected as being representative of typical metal-bonded parts. Significant quality and productivity problems were experienced during the manufacture of this and other similar parts. There are 13 main joints on the MLG door, made from 51 different part attributes, which create 38 different types of gaps [10]. Functionally, these joints are similar; however, in nature they are different.

The prefit process is selected for the modeling purpose because the maximum number of nonconformances occurred at this stage. Based on the number of joints and sequence of prefit steps, the process has been divided into 13 workstations. Therefore, 13 similar machines, named "action," have been created in the simulator. These machines are programmed to work on assigned joints at the

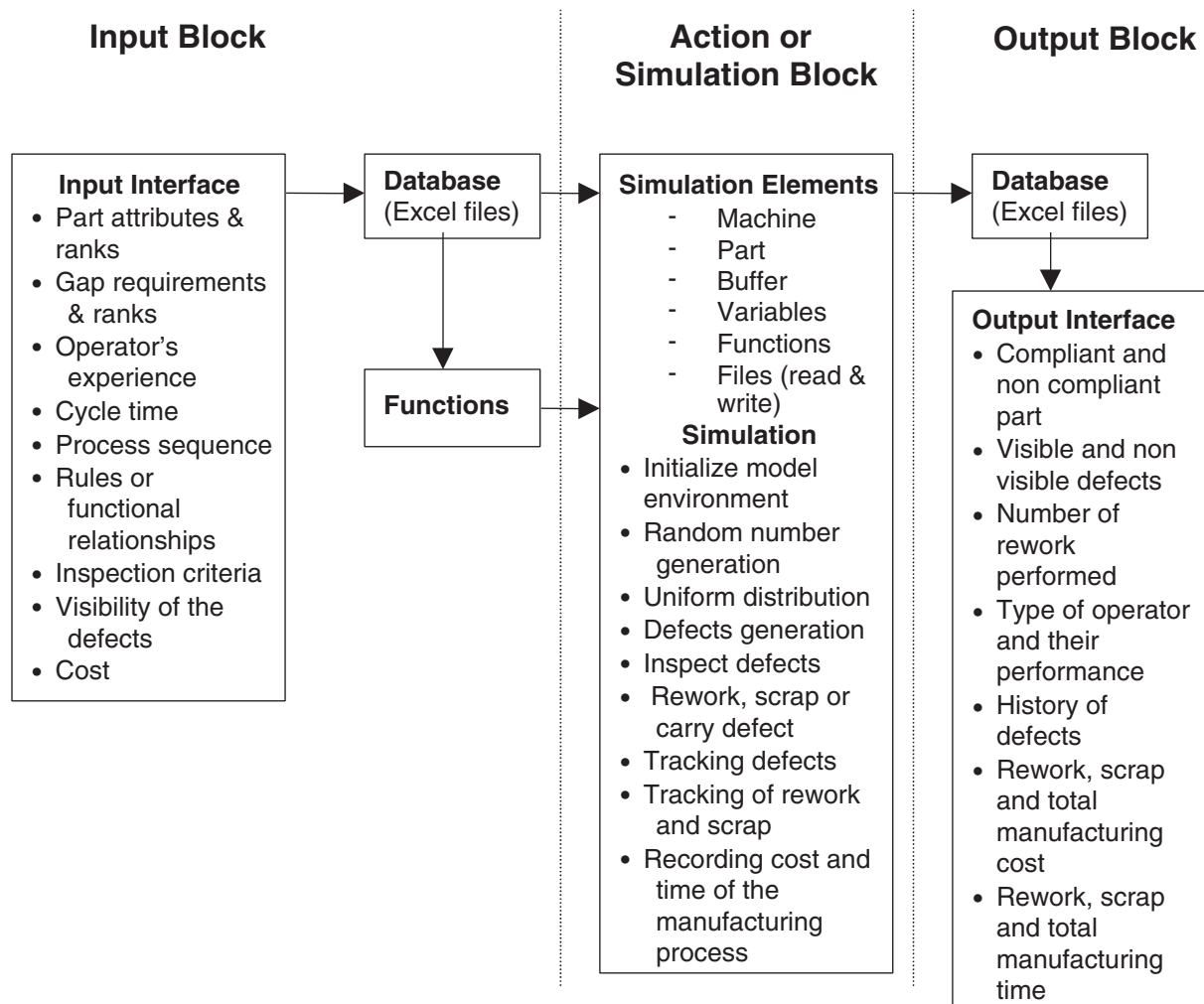


Figure 1. General structure of the simulation model

assigned machine. The operator with the assigned attribute profits the components, creates the required gaps, inspects these gaps, makes changes to noncompliant gaps, and moves the kit to the subsequent workstation.

Each of these machines works on real time, which is controlled by the cycle time. The cycle time for each workstation is defined in a file element, controlled by the “SOC” machine. The SOC machine reads the file and provides cycle time for each workstation in terms of a variable element. During the simulation, various events occur in a sequential manner. A general description of these events is given as follows:

- The simulation starts at real time = 0.
- The simulation reads input data (see Table 1) and records data for the model in the assigned variable arrays. Names of the 13 joints are defined and recorded in string variables.

It also initializes the variables after recording the results of simulation and before starting the next run.

- The SOC machine pulls the junk part to define the part flow. It also reads the cycle time for the workstation and provides the cycle time for each workstation.
- The INSTAG machine pulls the “kit” containing all parts and pushes it to the action machine for the manufacturing processes. The OP1 machine generates initial dimensional attributes for each part feature in the kit using the Fatt function. (A summary of various functions used in modeling the profit process for the metal-bonding part is given in Table 2.) The Fatt function at first generates a random number. This random number is then compared with the likelihood for rank of part dimensions to select the rank (between 1 and 5) for the part feature. Once the rank is selected, the part feature dimension is then randomly selected within the

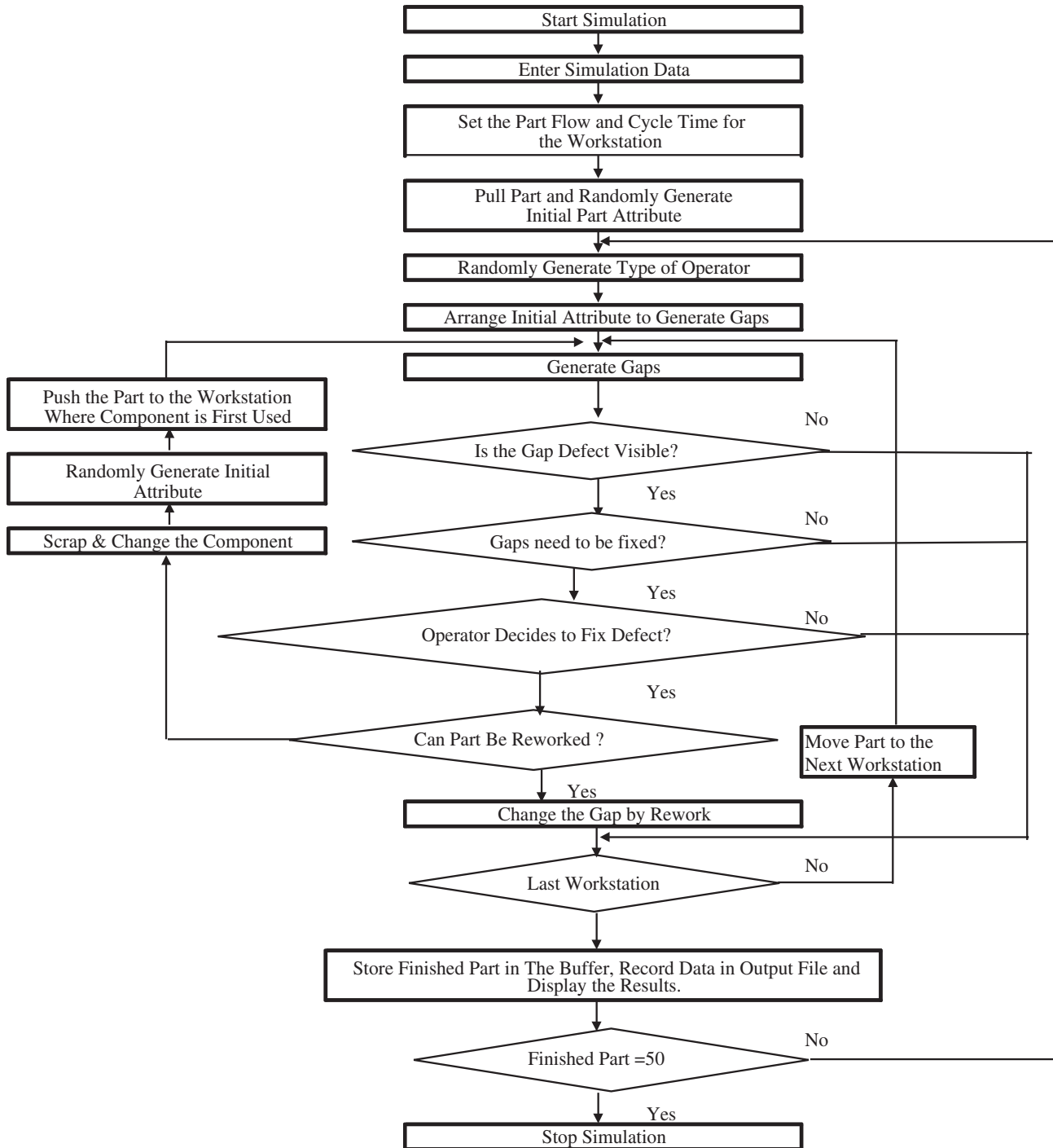


Figure 2. General flowchart of events during simulation

Table 1. A summary of simulation model input files (prefit process)

Input Files with Description	Variables to Read the File From
<i>Cycfile</i> : cycle time for each workstation	<i>c</i> : cycle time to finish tasks at each workstation
<i>Likeli</i> : likelihood chance associated with each primary variable	<i>li</i> : likelihood chance for the attribute associated with the incoming part <i>var</i> : total number of primary variables (attributes)
<i>Tol</i> : range of dimensional tolerances of 51 dimensions	<i>t</i> : real variable for the range of dimensional tolerances from the part drawing
<i>Ddli</i> : provides likelihood chance for the occurrence of a compliant gap after rework	<i>Dli</i> : real variable used for reading the rows and columns from the file
<i>Atype</i> : file related to the type of joints	<i>tyj</i> : types of joints associated with the primary variable <i>tyt</i> : types of transient joints associated with the primary variable <i>cseq</i> : to recognize the primary variable used in column order <i>rseq</i> : to recognize the primary variable used in a row order <i>comp</i> : types of components attached to the primary variables <i>var</i> : number of primary variables <i>act</i> : number of actions attached to the primary variable
<i>Gapeq</i> : has six columns related to the functional relationship between the primary variables	<i>tp1</i> , <i>tp2</i> , <i>tp3</i> : are related to the type of changes that affect the primary variable after rework <i>tp4</i> : represents the types of various joints <i>tp5</i> : presents the pattern of functional relationships in terms of equation type and number of variables <i>w3</i> : types of gap that are visible to the operator <i>tg</i> : tolerance requirement related to <i>tp4</i>
<i>Tgap</i> : tolerance requirement for the type of gap given by the customer	
<i>Tinsp1</i> : inspection-level criteria file for primary attributes based on operator's experience	<i>Inpa</i> : inspection criteria for primary variable (attribute of the part) based on operator's experience level
<i>Tinsp2</i> : inspection-level criteria file for gaps based on operator's experience	<i>Inpg</i> : inspection criteria for dependent variable based on operator's experience level
<i>Task</i> : provides detail related to the workstation	<i>task</i> : number of workstations <i>joi</i> , <i>nojai</i> : number of tasks (out of 38) performed at each workstation <i>tatt</i> , <i>tnoatt</i> : number of attributes (out of 51) used at each workstation <i>tnoatt1</i> : cumulative number of attributes used at each workstation <i>no</i> : number of attributes at each workstation <i>jj</i> , <i>jj2</i> : number of actual tasks performed, which has a direct effect on the quality

dimensional range allocated for that rank. Using uniform distribution and the defined range of the dimensional ranks, all 51 part feature dimensions are similarly created.

- After the creation of the dimensional attributes, the OPI machine generates the type of operator using the Funwork1 function. The Funwork1 function randomly selects an operator based on the assigned likelihood of their availability in a manner similar to that described above. In this simulation, a highly experienced operator is available 70% of the time, a medium-experienced operator is available 20% of the time, and a low-experienced operator is available 10% of the time.
- Simulation arranges the initial part attributes (using the Funcul function) by copying them to the variable arrays so that they can be displayed on the screen and calculations can be preformed easily.
- As the kit moves to the action machine, gaps are calculated with their ranks (using the Fungs function).

- If the gap rank is acceptable, the kit moves to the next workstation. On the other hand, if the gap is not acceptable, the kit stays at the workstation for the subsequent steps. In reality, however, at this stage the operator does not know whether the gap is acceptable and whether he or she needs to do anything to fix the gap. The results of simulation will assist the operator in making these determinations.
- Using the fun_v function, the simulation identifies if the defective gap is visible to the operator. If the defective gap is not visible, then the defect stays with the kit, and the kit moves to the next workstation carrying the defect. If the gap defect is visible to the operator, then the kit stays at the workstation for the next step.
- The operator must now determine whether the gap just created needs to be fixed. To assist him or her in doing so, the simulation considers (1) the operator's experience, (2) the accessibility/visibility of the problem, and (3) the inspection level/defined inspection method, with the aid

Table 2. A summary of functions used in modeling the prefit process

Name of Function	Description of the Function
Fungap	Once the rework is assigned, this function changes the initial attribute and generates the reworked gap. It also keeps track of changes to other gaps resulting from the rework to the gap being inspected.
Funwork1	Random selection of the type of operator
Funwork2	Based on the type of operator selection of inspection criteria for the attributes and created gaps
Funwork3	Based on the type of operator, how rework creates new gaps
Fund1	Once the operator decides to fix the problem, then, based on some other related factor, he or she can either leave it as is or do something about it
Fund2	If the operator decides to do something, then how he or she changes the gap
Fundis2	To display the dimension of the primary variable and scale on the screen
Fundis3	To display the dimension of the reworked primary variable and scale on the screen
Funcol	To arrange the primary variable for the workstation in a table to calculate the gap
Fungs	To calculate the gap rank from the created gap using the primary variables
Fun4	To calculate the gap rank for tp5=4 type of created gap using the primary variables
Fun6	To calculate the gap rank for tp5=6 type of created gap using the primary variables
Fun_v	Based on the visibility of the problem; creates operator's decision to do something or not
Funti	To calculate total processing time, rework time, and lost time due to the scrap
Fatt	To generate the primary attribute of the part using the likelihood function
Fchatt	If there is change in a component, then the primary attribute is generated using this function
Decision	To create 0s and 1s decision for the operator

of a *decision* function (called a decision switch) and the decision matrix.

- After considering the visibility of the defect and making the decision that the gap needs to be fixed, the simulation determines if the gap defect can be fixed. This decision or determination is based on the gap defect type and its rank, the operator's experience in fixing the defect, and the assigned likelihood of rework/scrap for various types of operators. Using the random number method and the assigned likelihood, the simulation then identifies if the operator can do something to fix the defect or leave it. If the decision is to leave it, then the kit will carry the defect and move to the next workstation. However, if the decision is to fix the defect, the kit will stay at the same workstation. Using the Fund1 function, a decision is then made either to rework the gap defect or to scrap and replace the part with a new one. If the decision is to scrap the part, then using the Fchatt function, a new part with new attributes is created at the same workstation where it was scrapped. Also, at this time, the kit must move to the workstation where this part was first worked on so that all gaps associated with this part are recalculated and reexamined.
- If the decision, however, is to rework the part, then the gap is corrected to bring it in compliance by using various functions for various types of gaps (e.g., Fungap, Fund2, Fun4, and Fun6). These functions essentially allow changing of the part feature attributes; by dressing, forming, or grinding, the operator changes the part attribute during actual manufacturing.
- After the rework, as the kit moves to the subsequent workstation, the simulation looks for the last workstation of the system. If it is not the last workstation, the part moves to the next workstation, and simulation repeats the steps starting from step 7. The process repeats until all parts are assembled and tested for the gaps to yield the complete prefit of the entire assembly.

- The finished prefit assembly is then stored in a buffer, and the results of simulation are appropriately displayed on the screen using the Fundis2, Fundis3, and Funti functions. The results are also stored in the output Excel file for subsequent analysis of data. The results also include the total cost and processing times associated with overall work performed besides the results on the quality of parts (gaps in this case).
- At the next step, new parts are similarly simulated until all 50 parts have been simulated and their results stored in the output file.
- Simulation then stops until the simulation of a new scenario needs to be run.

6. Validation of the Model

Validation is critical to the successful use of the model as a predictive tool and involves testing to ensure that the model accurately reflects the behavior of the real system. The model has two features that lend it to modeling human behavior and decision making during the manufacturing process: (1) it allows the modeling of a complex system by supporting modular construction, and (2) it has one-to-one correspondence with the physical world, thus easing the burden of model validation.

Furthermore, the model is verified using the base run model, simulation for 50 parts, and scenario analysis. Based on the input data provided to the model, the initial part feature dimensions created by the model were verified and found to be as prescribed by the likelihood functions (i.e., 90% of the time, these dimensions were within the acceptable tolerance).

Using the company's prevalent prefit practice, most of the gap defects escape the prefit process regardless of the

operator's experience or the level of inspection. Results of simulation clearly show that the specified part detail tolerances are not capable of producing compliant gaps, even from a theoretical viewpoint. Therefore, the process capability needs to be enhanced during the prefit process to adjust the gaps in such a way that both visible and non-visible gaps can largely be fixed during this stage without minimum or no escapes of defective gaps.

Overall, the developed model mimics real the prefit process in real production. The likelihood function and uniform distribution can be changed accordingly to calibrate the model.

7. Conclusion

The general structure of the simulation model is relatively simple and consists of an input block, an action or simulation block, and an output block. A framework for the structure of data is developed to make the simulation modeling simple and easy to understand. A code for the model in Witness for the entire prefit process has been developed in this work. The model takes into account the following:

- the as-designed part tolerances and the visibility of the problem (e.g., various types of bonding defects) associated with the as-designed part tolerances,
- various workstations within the process,
- human interactions (e.g., operator's experience),
- costs and times associated with each process element.

The model is very flexible and allows the following:

- easy changes (e.g., to inspection criteria, creation of gaps, sequence of tasks at the workstation, etc.) through various model elements and minor changes in programming;
- the manipulation or changing of input parameters (e.g., part dimensions, operator experience, etc.) by using random functions, likelihood functions, ranking of variables, and so on;
- analysis of various scenarios without changing the programming code for the model.

The results of the simulation provide a very powerful means of prompting the exact nature of the gap problems, where they occur, and how they could possibly be fixed, even before the parts are released for production. From the knowledge of the actual incoming detail part dimensions (supply side), one can create an exact map of the gap problems that must be fixed during the prefit stage. Such knowledge will also provide key indicators toward developing a strategy to satisfactorily fix the problems and minimize the cost. For example, from the knowledge of

the initial dimension of the mating parts that form a given joint and the gap these dimensions will create, one can easily deduce which detail must be adjusted and in what manner. The simulation model used in this work is capable of continuously tracking the overall quality, cost, and time aspects of the prefit process. However, one can choose any cost and time formulation for the model. Using the model, various scenarios can be analyzed to establish the optimal condition for supply-chain logistics for the company.

Finally, the model is a necessary analytical tool for supply-chain management to meet customers' requirements at a low cost and with minimum loss of time caused by the rejected and reworked product.

8. Acknowledgment

The project was cofunded by NSERC through a CRD grant.

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