

Assembly Process Improvement by Means of Inspection Planning and Corresponding Tolerance Planning – A Modelling and Simulation Approach

Der Fakultät Maschinenbau der Universität Dortmund zur Erlangung des akademischen
Grades eines

Doktors der Ingenieurwissenschaften

vorgelegte

Dissertation

von

Jirapha Liangsiri M.Sc.

aus

Bangkok, Thailand

Gutachter: Prof. Dr.-Ing. Horst-Artur Crostack

Gutachter: Prof. Dr.-Ing. Klaus Heinz

Tag der mündlichen Prüfung: 13 Dezember 2007

ACKNOWLEDGEMENTS

This doctoral study has been one of the most significant academic challenges I have ever faced. I would not be writing this acknowledgement without help, support, patience, and guidance of a lot of people. First, I would like to express my deepest gratitude to my mentor, Prof. Dr.-Ing. Horst-Artur Crostack, for his invaluable intellectual contributions and support despite his many other academic and professional commitments. His wisdom, knowledge and commitment to the highest standards inspired and motivated me. I am also deeply indebted to Prof. Dr.-Ing. Klaus Heinz, who had generously given me skilful comments and helpful advices for this dissertation.

Dr.-Ing. Robert Refflinghaus and Michael Saal contributed invaluable to this work. I sincerely appreciate the large amount of time that they had spent in providing feedback and supporting in all phases of this dissertation. I am grateful to Michael Höfling for his assistance in getting my research started on the right foot and also for his contributions in several papers that we wrote together. I would also like to thank all my colleagues at the Chair of Quality Management. Their collegiality and friendship had created a warm and inspiring atmosphere at work.

This dissertation was conducted at the Graduate School of Production Engineering and Logistics. I am grateful to the German Federal State of North Rhine-Westphalia who financed this research through a doctoral scholarship. I would like to thank my fellows from the Graduate School. I profited a lot from the doctoral seminars and colloquiums. Moreover, they offered me the wonderful friendship that I could not ask for more.

My stay in Germany felt like home because all of my Thai friends. I would like to thank them for their support, encouragement, humour and great food. Special thanks go to: P'Thin and Nidnan for priceless supports both emotionally and physically, P'Kamol for all the help and being my postman, Jod for always being there for me.

To Rodi – thank you for your love, support and patience. I would like to thank my father who has always supported, encouraged and believed in me. Finally, I would like to dedicate this dissertation to my mother whom I could not thank her enough for everything she has given me and for everything I am today.

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1. INTRODUCTION

The chapter introduces the overview of the topic dealt within this dissertation. It provides the reader with brief explanations of the research framework and its background.

1.1 PROBLEM FORMULATION

Nowadays it is unlikely that any producer or manufacturer will produce all the components needed themselves. The more usual case is that a producer will have several suppliers providing parts which have been manufactured to a specified tolerance. With the introduction of tolerances, it becomes possible for one producer to use components produced by another, since the specification of required tolerances assures the user that the ordered parts will fall within certain cut-off dimensions.

The variation of the products effects on cost and performance of the manufactured products. Excess cost or poor performance will eventually show up as a loss of market share. Tight tolerances can result in excessive process costs. On the other hand, loose tolerances may lead to increased waste and assembly problem. Therefore, the specification of tolerance limits on each dimension and feature of engineering drawings becomes a critical factor. Tolerances must be planned carefully in order to provide a common meeting ground where competing requirements can be solved. The task of tolerance planning is the finding of the optimum where the product can fulfil customer's requirement with optimum cost and time /Nürnberg99/.

The matter of tolerance planning for a single-component product is not difficult. The proper tolerance can be determined from the process distribution for the component. On the other hand, planning tolerances for a finished product consists of many components created by different processes is not an easy task since the quality of assemblies depends on the quality of the manufactured components to be assembled. The planner has to determine which combination of component tolerances is the best.

In order to improve overall quality, cost, and time in the production, only tolerance adjustment may not give a satisfy improvement. The improvement can be excelled when tolerance adjustment is done together with implementing a good inspection strategy.

Quality inspection can be a check made on each piece produced (100% inspection) or a check made on a statistical sample of the lot. It can also be performed by the operator or worker making the part or component, by a second person who is responsible for measuring only. These are the examples of parameters in inspection strategy. Each inspection strategy has its own pros and cons. Three important criteria resembling the tolerance planning are needed to evaluate the inspection strategies: quality, cost and time.

Solving this kind of problem that each criterion interacts with each other without any aid can be complicated and tricky. Therefore, a simulation is chosen as an approach to these tolerance and inspection planning problems particularly in manufacturing and assembly processes.

1.2 AIM AND FRAMEWORK OF THE DISSERTATION

This research was conducted under the supervision of quality engineering department. The main goal of this project was to develop a simulator which is able to assist in solving tolerance planning and the corresponding inspection planning problems in production processes, both in manufacturing and assembly processes. With this simulator, the tolerance analysis can be done at the same time as inspection planning. This leads to quality characterisation and improvement, cost reduction and shorter design and planning phases.

The following research questions were set up in the development of the simulator.

- How can the effect of manufactured quality on the assembled quality be captured and imitated in the simulator?
- How can the simulator illustrate the performance of each strategy in term of quality, cost, and time?
- How can the assembly process be improved by the simulator based on tolerance planning and inspection planning concept?

These questions are explored through this research project. The simulator was developed based on the concept of the existing simulator which was intended for manufacturing process. A mathematical model was developed and integrated into the simulator in order to include the effect of manufacturing process on assembly process. Thereafter, the simulator was validated together with a pilot company.

The dissertation is organised into five chapters. First, the reader is provided with an introduction to the research project. After that, the theoretical framework which provides the basis on inspection planning, tolerance planning and simulation as well as the related literature are presented in Chapter 2.

Chapter 3 aims to give an insight of the developed simulator starting from the concept to the preliminary validation of the simulator. The detailed description of the mathematical model and logic behind the simulator are also provided here.

In Chapter 4, the application of the simulator in a pilot company is described. The implementation was done in order to validate the function of the simulator in a real world situation. The use of this simulator in industry is also pointed out.

Finally, the contribution of this research is concluded in Chapter 5. This chapter also dedicated to future outlook relevant to this research.

2. STATE OF THE ART

This chapter is the review of literature related to this dissertation. First, some terminology and concept of inspection planning and inspection strategy are described. The simulation approach that used in this research is also presented. It aims to give the reader an introduction to the wide field of simulation.

The literature about simulation in quality inspection are gathered and summarised. The chapter includes the existing simulator called “QUINTE” and “QUINTE+” which were developed in house at Department of Quality Management, University of Dortmund. These simulators are the essential foundation for this dissertation. Later on in the chapter, the assembly process and the correlated research in simulation and assembly process are portrayed later on in the chapter. The second objective of this research was initiated from the problems in tolerance planning. Therefore, at the end of this chapter, the background of tolerance planning and the problems in tolerance planning such as problem in tolerance analysis and problem in tolerance allocation are summarised.

2.1 INSPECTION PLANNING – INSPECTION STRATEGY

2.1.1 Inspection

Inspection is defined as a conformity evaluation by observation and judgement accompanied as appropriate by measurement, testing or gauging /ISO9000:2000/. The inspection act typically includes measurement of an output and comparison to specified requirements to determine conformity /Gryna01/.

The inspection was traditionally done on incoming parts, materials and the final products in order to decide on the product acceptance. However, once a product is finished and it is found to be defective, the damage has already been done. The inspection disrupts or delays the production process, wastes parts and material, and adds unnecessary cost to the product but no value.

With the advent of Total Quality Management (TQM) principles and practices, the traditional role of inspection has largely been discredited. TQM practices focus on making certain that quality is achieved during the production process by continuous quality improvement, thus obviating the need for final inspection. However, an ideal TQM environment does not exist universally for all companies. Government regulations sometimes require inspection to ensure quality or customer may require independent inspections to guarantee quality. Therefore, initial and final inspections are still a major and important function for many companies.

Nowadays the purpose of inspection has changed from only a decision on product acceptance to many other purposes. Some of these include /Tapiero96/

- *Testing of reliability*: used to control a process, to detect defaults and to correct them. It is applied extensively when a product is new, when the quality manager deems it necessary, typically following complaints or the detection of problems once the product has been sold (usually returning to the producer in the form of complaints,

excess warranty payments and services). In these cases, fault detection is assigned to either materials, workmanship, product design or process operations, and usually an in-depth study of the problems detected follows. When problem causes are removed and no special problems are detected, reliability testing is reduced.

- *Special tests*: following clients' complaints, the introduction of new technologies or new products. In such cases, inspection tests are performed by sampling finished product lots.
- *Preventive inspection* is used when there is uncertainty regarding a process continued operating performance. Inspection is then used to improve the information available to management and detect problems before they occur. Furthermore, when the costs of non-quality are large, preventive measures can be efficient, detecting problems prior to system breakdown. Such inspection is becoming increasingly important due to the growth of preventive measures in TQM.
- To assure customers that "proper procedures" have been followed in ensuring that a lot shipped to the customers conforms to pre-specified standards (and thus both provide a signal for quality operation and reduce the chance that the seller-supplier will face punitive damages of various sorts of this were not the case).
- To rectify potential defects prior to a lot's shipment. This is often important in complex assembly products, which require integration tests after their final assembly.

The inspections which are considered in this research are the inspections within the production processes, both in manufacturing and assembly processes. They aim to provide the proof of freedom from defects as well as ability to meet the criteria of use.

2.1.2 Inspection planning

According to DIN 55350 /DIN55350-11/, inspection planning is defined as planning the quality inspection. The inspection planning is the activity of designating the stations at which inspection should take place and providing those stations with the means for knowing what to do plus the facilities for doing it /Gryna01/.

The activities in inspection planning can be divided into short term and long-term activities /Pfeifer02/. One of the short-term activities is the generation of inspection plan, which is a work instruction, which regulates the inspection procedures. The inspection plan also includes the planning of documentation of results and the processing of data. The programming of the measuring devices and monitoring of inspection equipments are also a part of short term inspection planning.

The long term inspection planning includes the activities such as the inspection method planning, the construction consultation, the staff training, the investment planning, the inspection plan support, and the provision of inspection equipments.

Inspection planning is done variously, such as, by inspectors, by inspection supervisor, or by special planners. The following are the more usual job conditions, which are decisive in deciding who does the planning /Juran70/:

- *Complexity of measuring the quality characteristic*: The inspection of simple or routine characteristics can be planned by the inspector himself. With added

complexity, the planning will require the knowledge of a skilled inspection specialist or engineer.

- *Complexity of the product:* For complex products having many interacting dimensions or components, the planning will require someone with knowledge of the functioning of the product, the relative seriousness of different characteristics, and the complete manufacturing sequence. This will likely be a quality control engineer working in conjunction with test specialists.
- *Purpose of the inspection:* Inspection for the purpose of product acceptance may require someone with knowledge of the functioning of the product (e.g. a quality control engineer), but inspection for process control purposes can often be planned by inspectors or inspection supervisors assigned to the process.
- *Size and organization of the inspection function:* As the function grows, separating the planning from the doing becomes justified. This leads to inspection planners who develop and standardize the most efficient practices for inspectors to use.

2.1.3 Procedure for the development of inspection plan

The inspection plan should be done at the beginning of product development phase together with process planning, in order to allow integration of the inspection planning into the quality planning /Pfeifer02/. An inspection plan is based on standards and guidelines, legal obligations and company procedures, technical documents, knowledge of the processed and customer's demand. The VDI/VDE/DGQ 2619 /VDI2619/ norm described the systematic procedure for setting up an inspection plan. This procedure can be summarized into ten main steps which are presented in Figure 2.1.

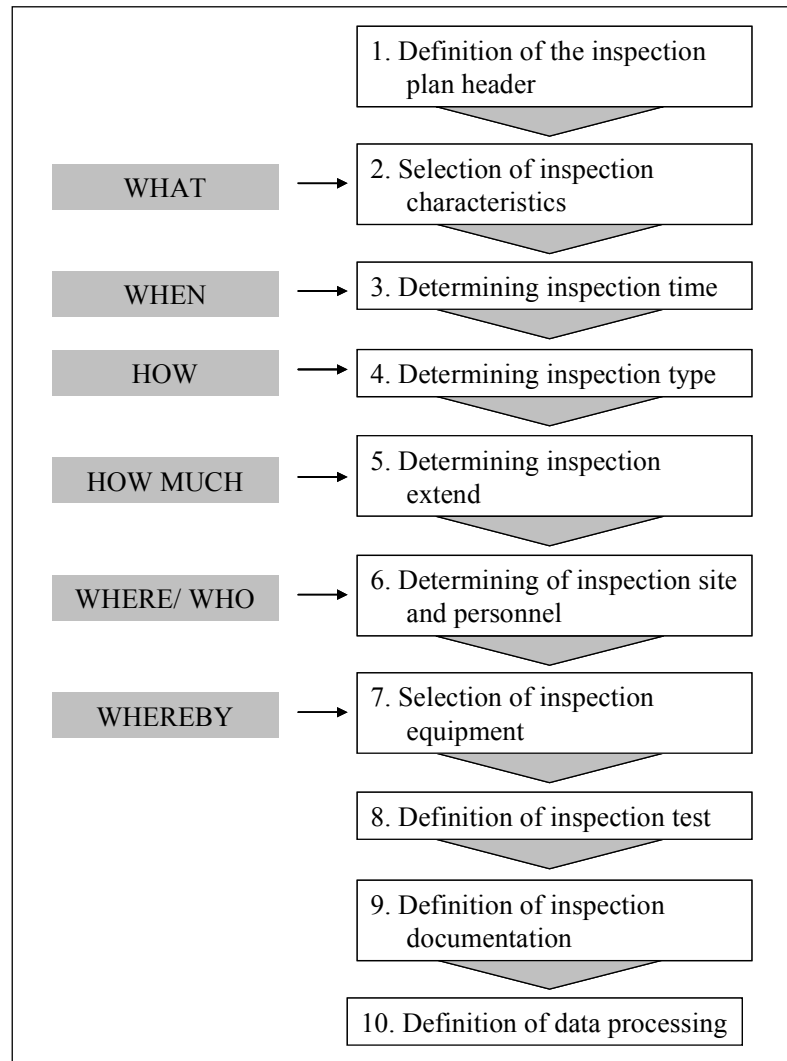


Figure 2.1: Sequence of inspection plan generation /Pfeifer02/

2.1.4 Inspection strategy

Inspection strategy is defined by Crostack /Crostack97/ as a valid principle for the whole production which specifies at least one aspect of the inspection planning. In this research, five main aspects are considered which are inspection type, inspection point (time), inspection extent, inspection location and personnel, and inspection equipment (Figure 2.2).

According to the last section, these five aspects must be defined after selecting the quality characteristics of the product that are needed to be inspected. The quality characteristic is the element building block out of which quality is constructed /Juran70/. Any dimension, chemical property, sensory property (e.g. taste, smell, feel, sound) which contributes to fitness of use is a quality characteristic. Still other characteristics are such properties as length of life, reliability, and maintainability.

The following part of this section describes the considered five main aspects in detail. The variation of each aspect gives different outcome in terms of quality, costs, and time.

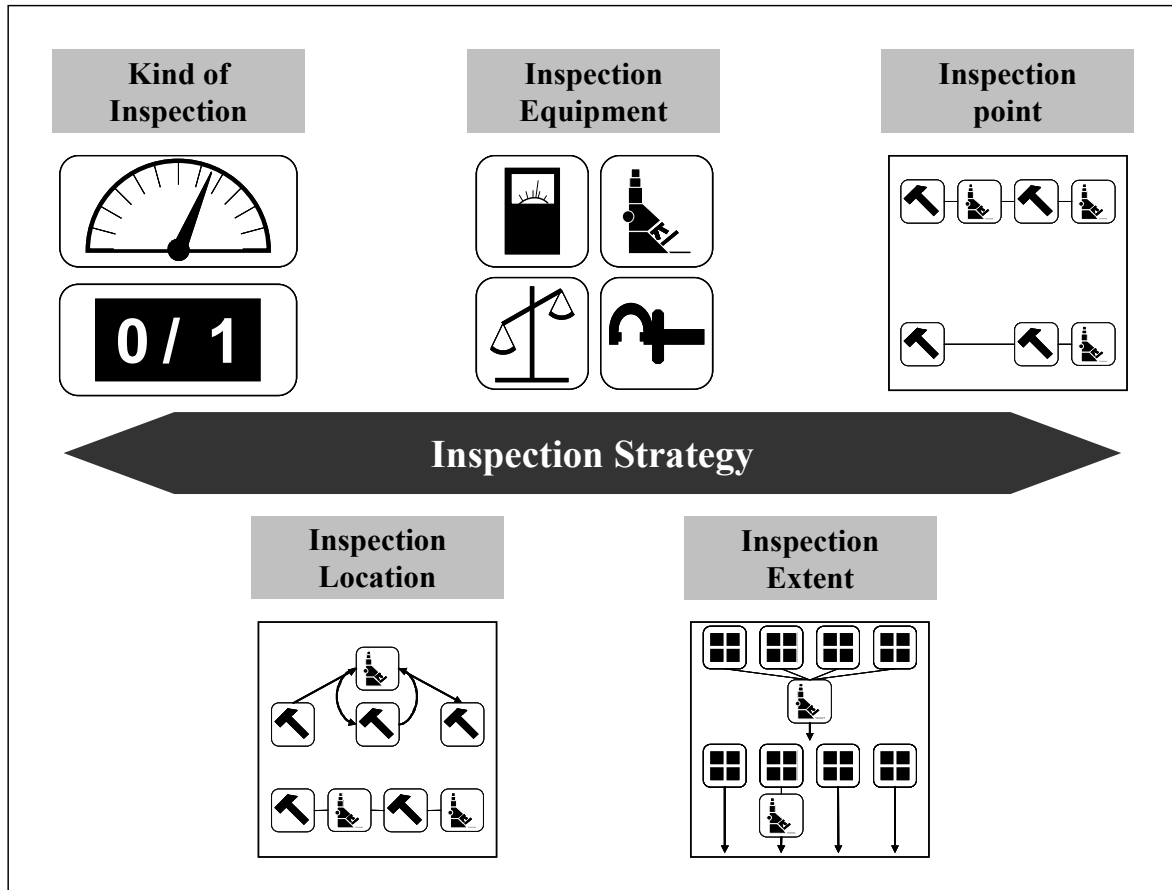


Figure 2.2: Considered aspects in inspection planning

2.1.4.1 Inspection type

The quality characteristic of a product can be evaluated using either an attribute or a variable measure. An attribute inspection evaluates the quality characteristic quickly with a simple discrete response such as good or bad, acceptable or not acceptable, yes or no, or conforming or nonconforming. It is suitable for quality characteristic such as colour, surface, texture, or perhaps even smell or taste.

A variable inspection obtains the quantitative value of the quality characteristic. It measures on a continuous scale such as length, weight, volume, or time. To select the method used in the inspection, cost, time and application should be taken into account. While the attribute method is usually simple and inexpensive, the variable method gives adequate information for purposes of process control.

2.1.4.2 Inspection point

The basic tool for choosing the inspection point is the flowchart. The most usual points are /Gryna01/:

- At receipt of goods from suppliers, usually called “incoming inspection” or “supplier inspection”.
- Following the setup of a production process to provide added assurance against producing a defective batch. In some cases this “setup approval” also becomes approval of the batch.
- During the running of critical or costly operations, usually called “process inspection”.
- Prior to delivery of goods from one processing department to another, usually called “lot approval” or “tollgate inspection”.
- Prior to shipping completed products to storage or to customers, usually called “finished-goods inspection”.
- Before performing a costly or irreversible operation, e.g., pouring a melt of steel.
- At natural “peepholes” in the process.

The earliest possible inspection point in the production is located right after the production of the characteristic. If an inspection is performed after every process, the scrap and rework cost are at a minimum because faulty items are identified before adding more cost to already defective material. The earlier in the production process that defective items are detected, the fewer the resources that will be wasted in subsequent stages in the process on products that may be thrown away or reworked. However, it is more expensive to conduct the inspection in this way than to combine the inspection of many quality characteristics at an inspection point. The reason for this is that the inspection time and cost, for example setup, queuing, and buffer, are high.

If many characteristics are inspected together later on in the process flow, the inspection time and cost will be lower. But then it results in higher scrap and rework cost. Therefore, if this intermediate inspection is done either too often or too late, unnecessary costs will occur.

The choice of the inspection point is based on number of criteria such as inspection costs, damage risk, accessibility of the characteristic, increase in the product value, etc. Also the fact that some parts cannot be inspected when they are already assembled must be considered.

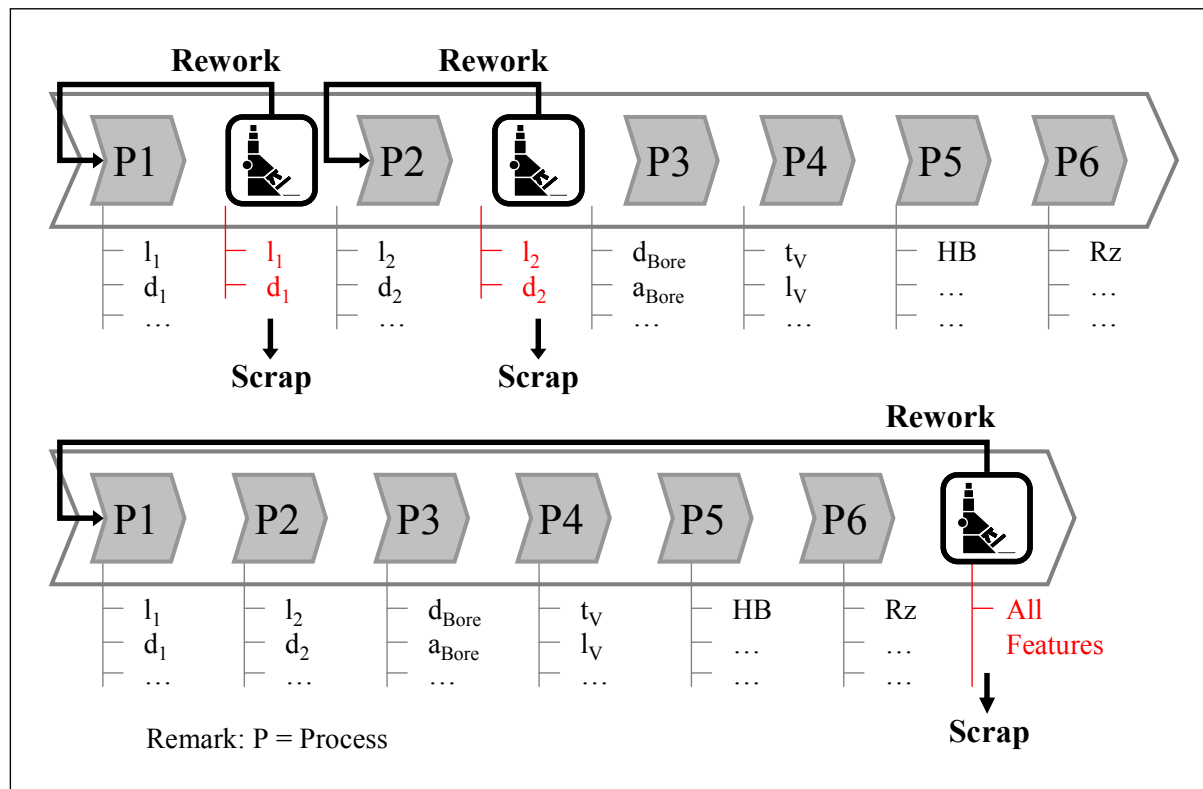


Figure 2.3: Variation of inspection point /Crostack04A/

2.1.4.3 Inspection extent

A decision about the extent of the measurement must be carried out. This aspect of inspection strategy directly influences inspection and failure cost. It ranges from no test to random and intermittent tests and all the way to a 100% test.

The 100% inspection is usually used for the final test of critical or complex products especially for safety relevant parts. It may also be used when the process capability is inherently too poor to meet product specification. To conduct 100% inspection is very costly and time consuming, even though the entire products are sorted. If the cost of delivery or of accepting a defective item is very high when compared to the cost of inspecting every item, the 100% inspection is a viable and possible preferred alternative. However, 100% inspection does not guarantee that no defective items will result. Human or equipment error in the inspection process can allow a defective item to escape. The limitations of 100% inspection are summarized in the following /Kehoe96/:

- It is not necessarily 100% accurate.
- It is not applicable where testing is destructive.
- It may actually reduce the quality level where the testing is intrusive or disruptive.
- A reduced pressure to get things 'right first time'.
- The cost may be prohibitive.

Sample inspection is carried out according to externally valid standards or company internal regulations. When choosing the inspection extent, the prior knowledge of the product is important, e.g., the importance of the feature for product quality, and process capability. The sample size must be of sufficient size to assess the quality of the process, part, or product. However, the larger the sample and the more frequently a sample is taken, the higher the cost will be.

No inspection is used when there is already adequate evidence that the product conforms, and hence no further inspection is needed. While no inspection or sample inspection gives benefits in inspection cost and time, the company should bear in mind that it includes the risk of declaring the lot good even if it might contain defects in the lot.

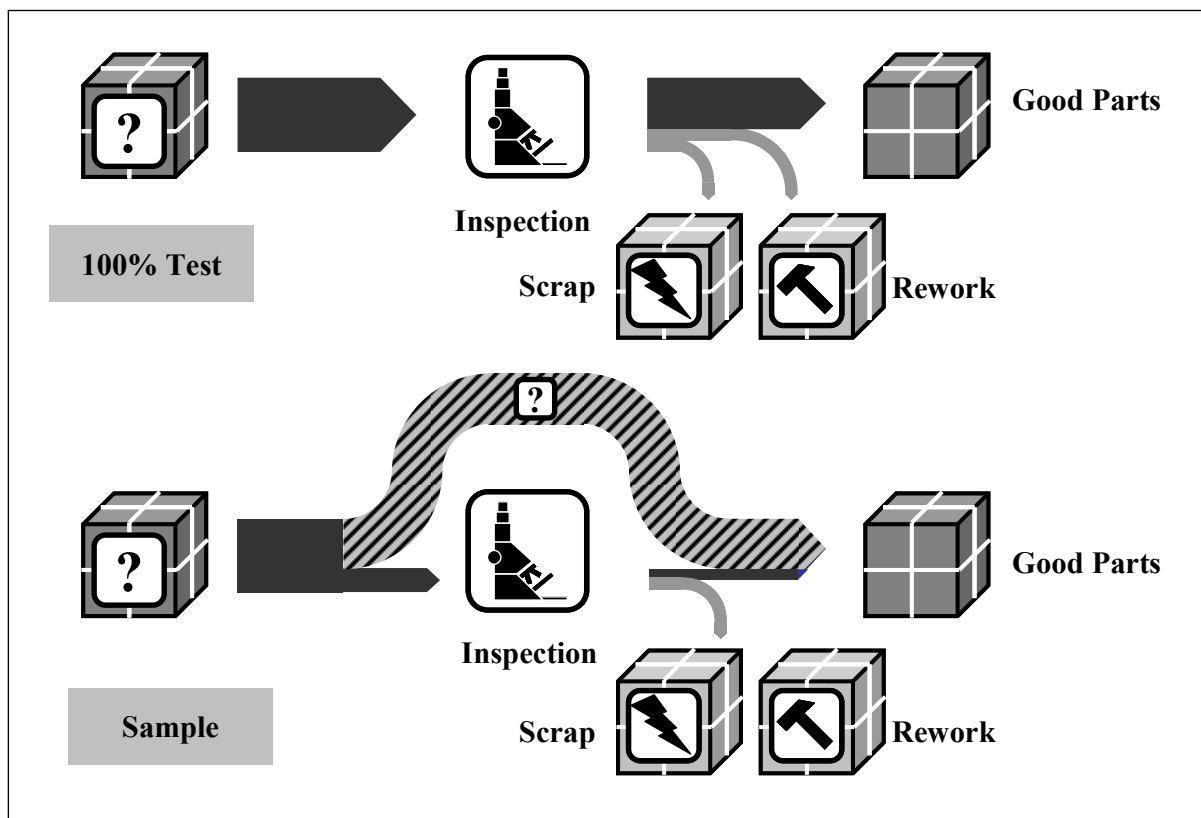


Figure 2.4: Variation of inspection extent

2.1.4.4 Inspection location and personnel

Inspection can be performed either at the process or at a special inspection location. In some cases, the operator may be the only person who should make the inspection. In other cases, the product might pass through an inspection or test station, where inspectors or testers make further inspections. Or such inspections might be made by automatic quality-control equipment and the data is automatically processed and used for adjustment of the process.

If the inspection is performed at the process, the advantages are that no transportation is necessary and the feedback on error can be done quickly. Moreover, the inspection result can be used to determine if the production process is functioning properly. Correcting a quality

problem during the production process will reduce the number of potentially defective units of finished product. However, it is not economical to have testing equipment at every production process or line, if the testing equipment is expensive.

On another case, if the inspection is conducted at a special inspection location, the accuracy and capability of the inspection processes are higher as the inspection environment can be controlled. However, the cons of this alternative are higher transportation cost and higher cycle time since the parts have to be transported and wait for inspection.

In an ideal TQM environment the operator serves as the inspector, inspecting items as they come through the process and taking immediate corrective action /Russel95/. An adjunct to this approach is the use of “poka-yoke” devices as part of the self-inspection. These devices are installed in the machine to inspect process conditions and product results and provide immediate feedback to the operator. However, this is not always feasible. Inspecting parts may be time consuming and slow down the process too much if the operator inspects. Therefore, the machine utilisation can decrease, which can increase cycle time and manufacturing cost as well. The accuracy of inspection might be low since worker has to do both operating the machine and inspecting the parts. Moreover, to conduct an inspection, special skills or training may be required.

If the inspection is performed by an inspector or quality controller, the production process is not interrupted and the machine and operator utilisation can be better. However, there is an extra expense on personnel and the feedback on inspection result might not be done immediately.

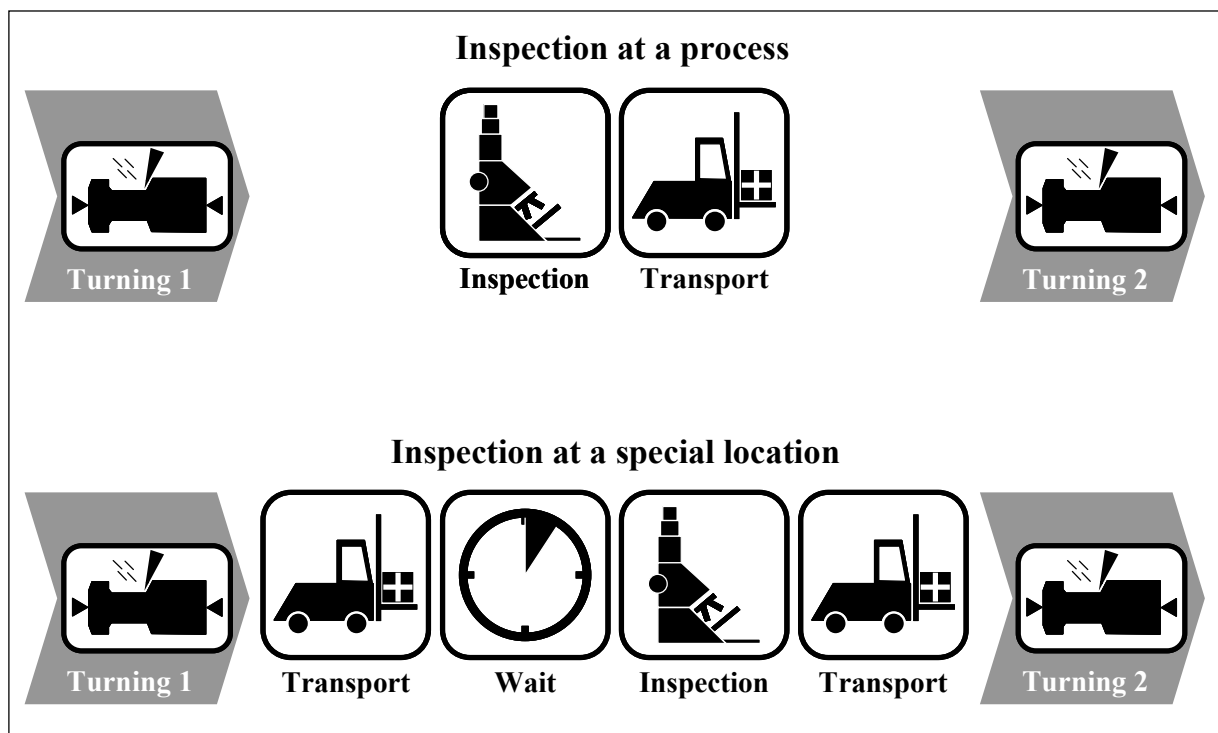


Figure 2.5: Variation of inspection location /Crostack04A/

2.1.4.5 Inspection equipment

The capability of the inspection device (measurement accuracy) and the tolerance of the inspected characteristics are the main selection criteria. Furthermore, acquisition cost, capacity and other elements such as type of inspected characteristic, type of obtained data, required training for the inspector, inspection time, are taken into account. Most of the time, high capability devices are expensive and difficult to handle.

As mentioned above, the inspection strategies have significant effects on the performance of production processes in terms of production cost, cycle time, and product quality. These impacts vary from one inspection strategy to another. Therefore, choosing a good inspection strategy can be a complicate decision. The inspection of a single process can influence the other processes in the production in such a way that would hardly be possible to predict the effects of different inspection strategies analytically. Thus, simulation can be a powerful tool to evaluate various inspection strategies. The modelling and simulation approach is described in Section 2.2.

2.2 THE APPROACH – MODELLING AND SIMULATION

2.2.1 General scientific problem solving process

Looking at the model-based approach to scientific problem solving from a very general point of view, the same pattern of actions can be observed. Starting with the real world situation, a problem which needed to be eliminated or improved is identified. To tackle this problem using scientific methods, a model is first built, and tries to find a solution of the problem in the world of the model. The obtained solution in the model world has to be interpreted in the real world and finally the solution has to be implemented in the real world to eliminate the problem. The process is shown in Figure 2.6 /Prähofer92/.

This pattern is common to all model-based activities. The way through the model taken in the problem solving process is essential. It does not matter if the real system exists or is to be built or if the system is a natural or an artificial one. Also, it does not matter if the model is expressed in some sort of formal language, like mathematics, or an informal description is used.

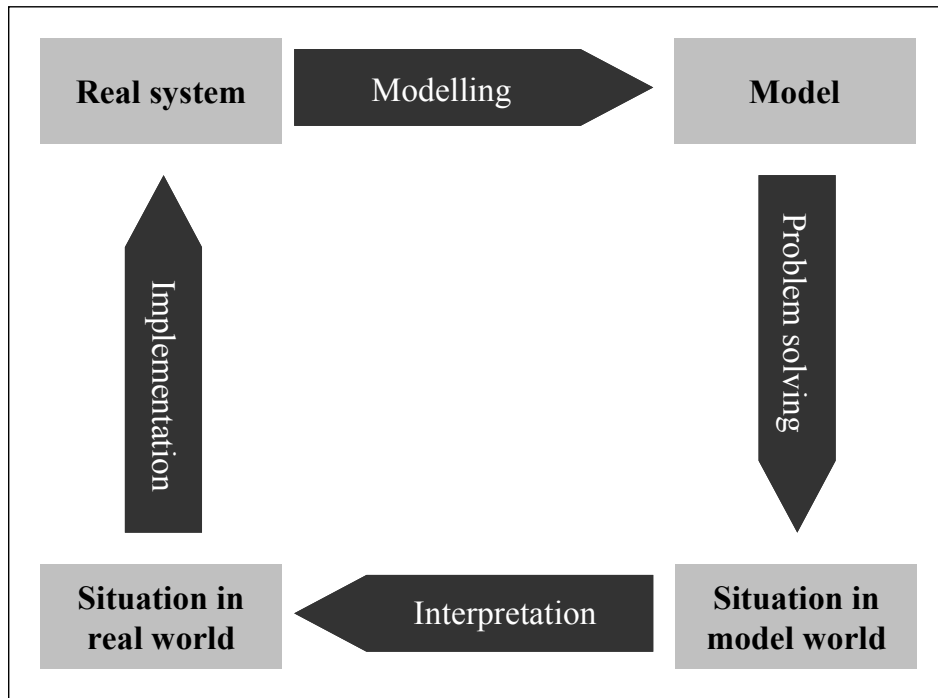


Figure 2.6: General problem solving process

Model building is the process of deriving a model of real system from some given information of the real system. This is not a trivial task. The main reason for that is that through the complexity of the real system it is impossible to comprehend and represent a real system as a whole or even to get complete information of it. Although model building is much easier for artificial systems or systems to be designed, this is even true here because uncertainties in the physical realisation always exist. A real system therefore should be conceived as nothing else as an infinite source of observable data from which in finite time we are able to retrieve just a finite portion.

Model building always means idealisation, abstraction and simplification. The question if the model, the simplified, idealised representation of the real system, is a valid representation of the real system is crucial and always should be answered in connection with specifying the purpose the model is built for- the objectives of the problem solving enterprise. So a model validly represents a real system according to particular objectives. A model may be valid to answer a particular type of question of a real system while it may fail to answer another. Hence, the model building process always should be guided by the objectives at hand and should prescribe the level of abstraction and simplification needed to answer the questions. Always the most simple and most abstract level that is still appropriate should be taken to reduce model and problem solving complexity.

Management scientists use a wide variety of tools and techniques to model, analyse, and solve complex decision problems like optimisation problems. These tools include linear programming, decision analysis, queuing theory, forecasting, and simulation. Two main different types of problem solving methods are distinguished:

- Analytical methods
- Simulation

Every problem-solution technique known to humanity were not described and recommended where they should be used in this part of the dissertation. Analytical and simulation methods are described in the following section. The research of Lydie /Lydie00/ recommends that the analysts at least consider alternative solution techniques. They should also give some consideration to the cost of using a particular solution technique compared to the potential benefits of the eventual solution. Unfortunately, identifying the best solution methodology is not always an easy task. If the analysts determine that a specific methodology might give them the best answer, but they have never used that technique, then this might not be the best time to experiment. Therefore, the analysts should use the solution methodologies that they feel more comfortable using. It will most likely give the most cost-effective solution.

2.2.2 Analytical and simulation methods

In analytical problem solving, the solution is deduced by employing inference rules which are known to be valid in the language the model is formalised in. The solutions are of general form in the sense that they allow generally valid statements about the problem. Individual solutions can be derived from them by replacing the symbolic coefficients of the general solution by individual values.

There are possibilities of building and using a mathematical model of the system to solve the problem. Optimisation techniques such as linear programming, goal programming and dynamic programming are valuable when a single goal is desired for minimisation or maximisation. Another technique is queuing theory. Queuing theory is the theoretical study of waiting lines, expressed in mathematical terms including components such as number of waiting lines, number of servers, average wait time, number of queues or lines, and probabilities of queue times' either increasing or decreasing. In some situations, queuing theory can result in simple formulas from which the user can get a lot of insight. It is largely recognised that queuing theory can prove valuable as a first-cut approximation to get an idea of where things stand and to provide guidance about what kinds of simulations might be appropriate at the next step in a project.

Many of the analytical tools often require the analyst to make some highly simplifying model assumptions. For instance, many queuing models assume that arrival rates follow a Poisson probability distribution, leading to elegant mathematical solutions. Other tools, such as linear programming, apply only to restricted types of problems. Linear programming applies to well-structured situations that can be modelled with a linear objective function and linear constraints and do not include probabilistic elements. Furthermore, the typical assumption is all data are known with certainty. Unfortunately, this is seldom true in practice. Real situations rarely meet the assumptions of analytical models. Often the more elegant the mathematical formulation of a problem is, the less matches reality /Evans98/. Therefore, the applicability of analytical methods is restricted.

Another shortcoming is the fact that optimisation techniques are limited to achieving the best results for only one goal, thereby sacrificing other secondary goals that maybe very important.

Finally, most mathematical models cannot satisfactorily cope with dynamic or transient effects of the real business environment and provide little information about the behaviour of the systems they model. For example, with static analysis techniques such as queuing theory,

the average waiting time and number of units in queue are known but there is no way to further examine the data.

Thus, although queuing theory, linear programming, and other analytical methods have many important practical applications, particularly as planning tools, they may not always be an effective analysis tools.

For situations in which a problem does not meet the assumptions required by standard analytical modelling approaches, simulation can be a valuable approach to modelling and solving the problem. Simulation is particularly useful when problems exhibit significant uncertainty, which generally is quite difficult to deal with analytically. It also allows the analyst to examine multiple goals simultaneously.

Moreover, simulation offers a problem solving method to obtain insight into the behaviour of the system and analyst can track the performance of a system with respect to several factors. Simulation tracks the event as they occur, keeping all time-related data for reporting purposes. The information available about the operation of the system is more complete with simulation than other techniques. For example, the average waiting time and number of units in queue are known, as well as the minimum and maximum values, the confidence interval on the range of these values, the histogram of the distribution of the data, and the time plot of the values.

However, simulation should not be used indiscriminately in place of valid analytical models. Many situations exist when approaches such as linear programming or queuing theory are more appropriate. The task of the modeller is to understand the pros and cons of different approaches and use them appropriately.

2.2.3 Definition of simulation

Simulation is one of the most powerful analysis tools available to those responsible for the design and operation of complex processes or systems. Many definitions are used to describe simulation. Pegden, Shannon and Sadowski /Pegden95/ described simulation as the process of designing a model of a real system and conducting experiments with this model with the purpose of either understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion set of criteria) for the operation of the system. A model is a representation of a physical process and possesses the essential attributes of that physical process /Colella74/.

Simulation can also be referred as a broad collection of methods and applications to mimic the behaviour of real systems, usually on a computer with appropriate software. In fact “simulation” can be an extremely general term since the idea applies across many fields, industries, and applications. These days, simulation is more popular and powerful than ever since computers and software are better than ever /Kelton98/.

Simulation models can be categorised to three types /Prähofer92/:

- Physical simulation models
- Graphical simulation models
- Computer simulation models

Physical simulation models are actual, physical re-implementations of the real world system, which is either to be built more easily or to be handled and experimented with more easily. Graphical model is a pictorial representation of the real system.

Computer simulation refers to methods for studying a wide variety of models of real world systems by numerical evaluation using software designed to imitate the system's operations or characteristics, often over time. From a practical view point, simulation is the process of designing and creating a computerised model of a real or proposed system for the purpose of conducting numerical experiments to give us a better understanding of the behaviour of that system for a given set of conditions. Although it can be used to study simple systems, the real power of this technique is fully realised when we use it to study complex systems /Kelton98/.

Pidd /Pidd92/ also stated that the basic principles of computer simulation are simple. The analyst builds a model of the system of interest, writes computer programs that embody a model and uses a computer to imitate the system's behaviour when subjected to a variety of operating policies.

The general nature of simulation offers a wide range of possible applications for different decision-making task. According to the degree of intervention the decision maker is able to exert on the real system, there are four levels in which simulation models can be employed /Prähofer92/:

- Explanatory
- Forecast
- Improvement
- Design

In the first level, the simulation describes the behaviour of systems in order to get more insight of the real systems. In the forecast level, a simulation model of an existing system is used to get information as to how it will behave in the future. Simulation can also be used to construct theories or hypotheses that account for the observed behaviour, which leads to the third level. In the third level, a model of an existing real system is used to analyse its operation and then to study different alternatives for improvement. No real system exists in the design level and the models serve as design blueprints which are tested by simulation.

2.2.4 Different kinds of simulation

Kelton /Kelton98/ classified simulation model along three dimensions. Simulation can be static or dynamic, deterministic or stochastic and continuous or discrete.

2.2.4.1 *Static vs. dynamic*

A model that describes the behaviour of the system through time is called a dynamic model. A model that portrays the behaviour of a system at a single point in time is called a static model. The difference is analogous to a still photograph versus a movie. Most operational models are dynamic. Many static simulation models are run using spreadsheet or financial software.

2.2.4.2 Deterministic vs. stochastic

Deterministic simulation models ignore the presence of random variation in the system being modelled, assuming it to be unimportant to the decision to be made. However, very few real world systems are free from the influence of random or unpredictable variables in the environment or in its own component. Stochastic models, on the other hand, explicitly try to capture the important random components of the system. A model can have both deterministic and random inputs in different components. Stochastic models produce uncertain output, which is a fact that must be considered carefully in designing and interpreting the runs in a project.

2.2.4.3 Continuous vs. discrete

In a continuous model, the state of the system can change continuously over time. In a discrete model, change can occur only at separate points in time, such as a manufacturing system with parts arriving and leaving at specific times, machines going down and coming back up at specific times, and breaks for workers.

There can be elements of both continuous and discrete change in the same model, which are called mixed continuous-discrete models or combined model.

2.2.5 Simulation modelling methods

There are four major simulation methods used by simulation community /Pidd98/:

2.2.5.1 Process-interaction method

In this method, the computer program simulates the flow of an object through a system. The object moves as far as possible in the system until it is delayed, enters an activity, or exits from the system. When the object's movement is halted, the clock advances to the time of the next movement of any object. This is the method that Arena, which is the simulation software in this research, uses.

This flow, or movement, describes in sequence all of the states that the object can attain in the system. Each state and event is simulated.

2.2.5.2 Event scheduling method

The basic concept of this method is to advance time to the moment when something happens next. An event usually releases a resource. The event then reallocates available object or entities by scheduling activities in which they can now participate. Time is advanced to the next scheduled event and activities are examined to see whether any can now start as a consequence.

2.2.5.3 Activity scanning method

The third simulation modelling structure is also known as the two-phase approach. Activity scanning produces a simulation program composed of independent modules waiting to be executed. In the first phase, a fixed amount of time is advanced or scanned. In phase two, the system is updated if an event occurs. Activity scanning is similar to rule-based programming.

2.2.5.4 Three-phase method

In the first phase of this method, time is advanced until there is a state change in the system or until something happens next. The system is examined to determine all of the events that take place at this time. The second phase is the release of those resources scheduled to end their activities at this time. The third phase is to start activities, given a global picture of resource availability.

2.2.6 Advantages and disadvantages of computer simulation

The main advantage of simulation is its ability to deal with very complicated models of correspondingly complicated systems. Since the basic concept of simulation is easily comprehended, a simulation model is often easier to justify to management or customers than some of the analytical models. This makes simulation a versatile and powerful tool. In addition, simulation might have more credibility because its behaviour has been compared to that of the real system or because it has required fewer simplifying assumptions and thereby has captured more of the true characteristics of the real system /Pegden95/.

Even though simulation has many strengths, it is not without draw backs. Virtually all simulation models are so-called input-output models. They yield the output of the system for a given input. Simulation models are therefore “experimenting” rather than “solving” the problem. They cannot generate an optimal solution on their own as analytical model can. They can only serve as tools for the analysis of system behaviour under specified conditions. The exception is a simulation model used to find the optimum values for a set of control variables under a given set of inputs. The following lists summarize some of benefits as well as drawbacks that are associated with simulation.

2.2.6.1 Advantages

- New policies, operating procedures, decision rules, information flows, etc. can be explored without disrupting ongoing operations of the real system.
- New hardware designs, physical layouts, transportation systems, etc. can be tested without committing resources for their acquisition.
- Developing simulation model increases understanding already.
- Taking uncertainty into account.
- Detection of unforeseen problems or bugs.
- Diverse systems can be described realistically.
- Answer “what-if” question, particularly useful in the design of new systems.
- Enhances creativity, especially in the design of the system.
- Simulation is more convincing than mathematical formulas.
- Simulation is easier to understand than many analytical approaches.
- Time can be compressed or expanded allowing for a speed up or slow down of the phenomena under investigation.
- Insight can be obtained about interaction of the variables.
- Insight can be obtained about the importance of variables on the performance of the system.
- Bottleneck analysis can be performed indicating where work in process, information, materials, etc. are being excessively delayed.

- It is an effective training tool.
- It is able to deal with very complicated models of correspondingly complicated systems.
- The improvement in performance/price ratios of computer hardware, making it ever more cost effective than the past.
- Advances in simulation software power, flexibility, and ease of use have moved the approach from realm of tedious and error-prone low-level programming to the arena of quick and valid decision-making.

2.2.6.2 Disadvantages

- The results are uncertain in stochastic simulation. Many real systems are affected by uncontrollable and random inputs. Therefore, the outputs from many simulation models, which involve random, or stochastic, input components, are random as well.
- Model building requires special training.
- Simulation results maybe difficult to interpret.
- Simulation analysis can be time consuming and expensive.
- Hidden critical assumptions may cause the model to diverge from reality.
- Correctness of results is hard to prove.
- No guarantee for optimal solution.

2.2.7 Steps in simulation study

Computer simulation involves experimentation on a computer-based model of some systems. The model is used as a vehicle for experimentation, often in a “trial and error” way to demonstrate the likely effects of various policies. Thus, those, which produce the best results in the model, would be implemented in the real system. Figure 2.7 shows the basic idea.

In order to conduct every simulation studies, good problem-solving techniques should be merged with good software engineering practice. Figure 2.8 shows a set of steps to guide a model builder in a thorough and sound simulation study.

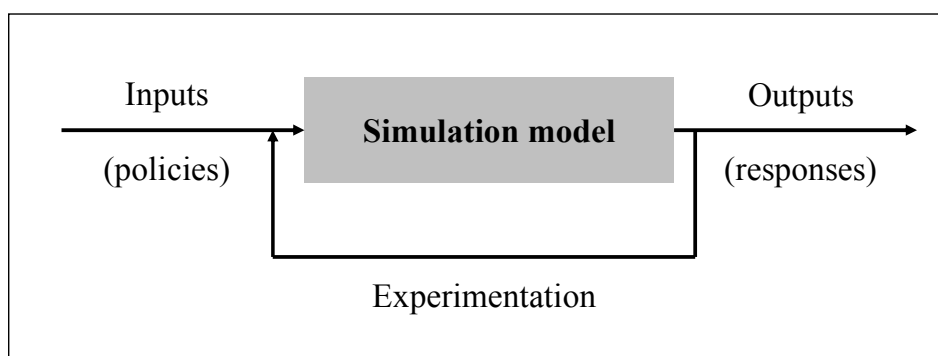


Figure 2.7: Simulation as experimentation /Pidd92/

2.2.7.1 Problem formulation

The first step in every simulation study is to define and formulate the problem. Problem definition can either provide by the policy maker, those that have the problem, or being

developed by the analyst. The analyst can be confronted with large variety of problems. Many simulation studies deal with systems that are not meeting the client's expectations. Other simulation studies are not focused on a known problem, but are trying to avoid a potential future problem especially when simulation is used to help design a new system. In spite of that, simulation studies can be focused on a system that has been completely designed but not yet constructed or implemented. In this case, simulation is used to verify the system.

However, the initial problem is rarely defined clearly, so the problem definition needs to be developed by the analyst together with those who have the problem and ordered the study. Both side need to agree on the problem definition and its formulation. At the same time, the initial bounds on the size of the system can be placed for the purpose of the study. During the conduction of the study a re-formulation of the problem definition might become necessary due to new important aspects that may not have been known before and that need to be considered now.

2.2.7.2 Setting objectives and overall project plan

The objectives indicate the questions to be answered by simulation. At this point a determination should be made concerning whether simulation is the appropriate methodology for the problem as formulated and objectives as stated. Due to the complexity of system considered in this dissertation and the advantages of computer simulation over other analytical methods, it is decided that simulation is the appropriate methodology.

The overall project plan should include the plans for the study in terms of the number of people involved, the cost of study, and the number of days required to accomplish each phase of the work with the anticipated results at the end of each stage.

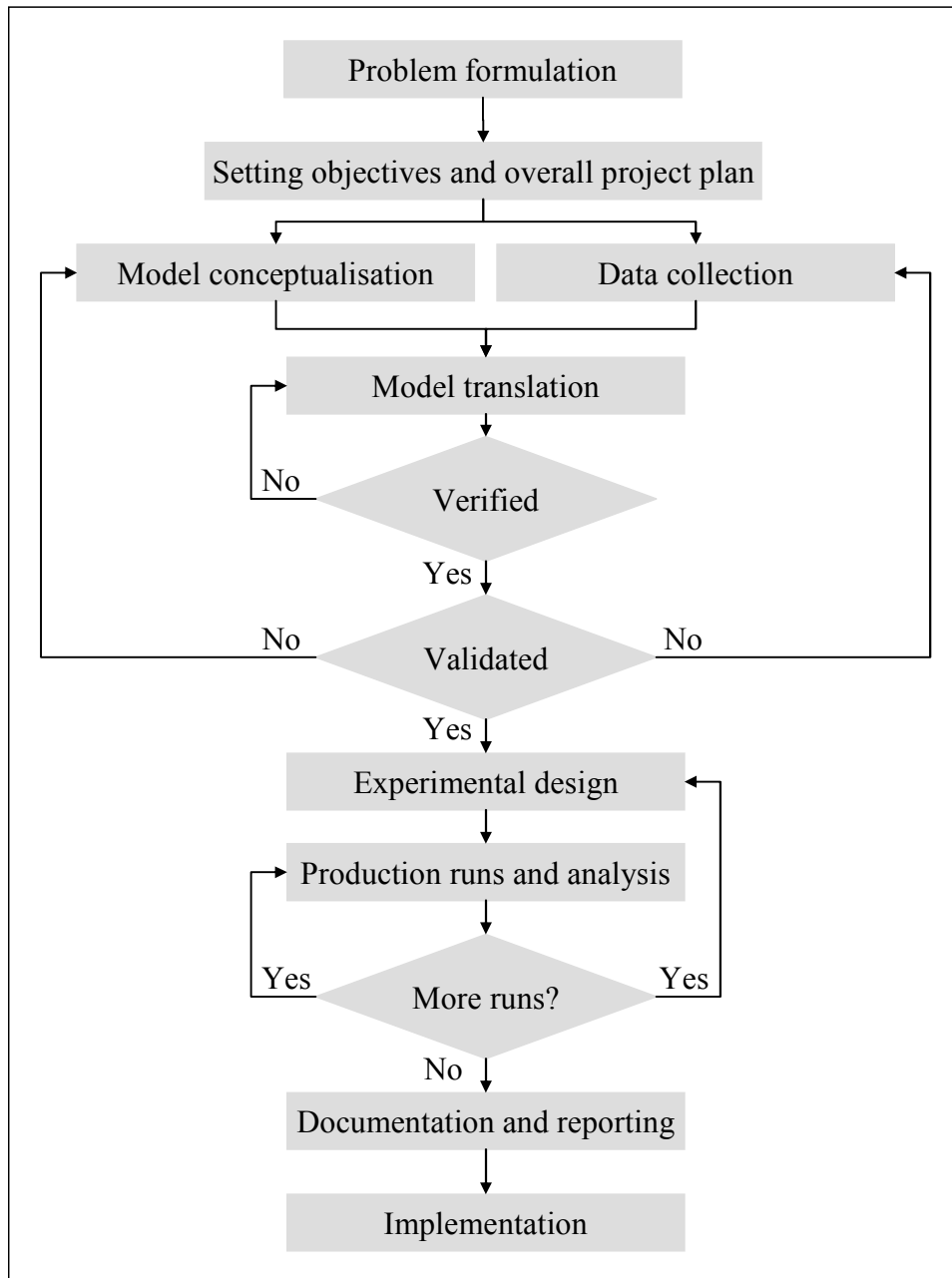


Figure 2.8: Steps in simulation study /Banks00/

2.2.7.3 Model conceptualisation

It is very important not to rush on to the computer and start modelling as soon as the objectives are defined. Some time should be spent on the formulation of the model design. Some of the things that should be taken into consideration are the data structure or constraints, the type of analysis to be performed, the type of animation required, and current comprehension of analyst.

The art of modelling is enhanced by having abilities in abstracting the essential features of a problem, selecting and modifying basic assumptions that characterize the system, and then enriching and elaborating the model until a useful approximation results.

Thus, it is the best to start with a simple model and build toward greater complexity. On the one hand, the model should be as simple as possible for the ease of understanding, ease of formulation, and computational efficiency. On the other hand, the model should be as accurate as possible. However, the model complexity need not exceed that required to accomplish the purposes for which the model is intended. Violation of this principle will only add to model-building expenses. The definition of model boundary is usually a trade off between accuracy and cost. The greater the degree of detail to be modelled, the more precise and expensive the required input data. Therefore, the model must include only those aspects of the system relevant to the study objectives. It is not necessary to have a one-to-one mapping between the model and the real system. Only the essence of the real system is needed.

It is advisable to involve the model user in model conceptualisation. This will both enhance the quality of the resulting model and increase the confidence of the model user in the application of the model.

2.2.7.4 Data collection

Simulation project cannot be carried out without input data. There is a constant interplay between the construction of the model and the collection of the needed input data. As the complexity of the model changes, the required data elements may also change. Also, since data collection takes such a large portion of the total time required to perform a simulation, it is necessary to begin it as early as possible, usually together with the early stages of model building. The objectives of the study dictate, in large way, the kind of data to be collected.

The collected data can serve three different purposes /Robinson94/:

- To build the simulation model
- To check validity of the model
- To set the initial levels of the experiment factors

Since the input data plays important role in simulation project, it is important that precise input data is used in the modelling. Building a valid model and feeding it with inaccurate input data or analysing the output data inappropriately will never yield any valuable result.

If the model represents a system that already exist, historical data can be collected to feed the model. However, data is not always available immediately. In some cases, data might not be obtained at all. If the required information is not available and not obtainable, data estimation is one approach to find a solution. Data can be estimated by looking at similar situations or facilities or by using knowledge of the experts. The sensitivity of this input must be checked in the validation phase to ensure that the input is not critical.

The historical data can be collected and re-used in the same manner in the model, which is called data streams. It is a great help for the validation of the model. However, the data streams represent only a short period of time, and only this precise set of circumstances can be modelled.

One of the great advantages of simulation is its ability to cope with randomness of the events. If the inputs are to be modelled as random, it must be decided which distribution to derive from the data. The distribution can be standards or user-defined. The standard distribution is

completely general regarding the set of circumstances modelled and represents perfect randomness. Conversely, Random input data always leads to random outputs; therefore it is suggested to be cautious when using standard distribution.

2.2.7.5 Model translation

Once the conceptual model and data are ready, the model must be entered into a computer-recognisable format. The analyst must decide whether to program the model in a simulation language or to use special-purpose simulation software. Being familiar with the software used is a key factor in determining the time required for this phase of the project.

In most case, it is recommended to start building a portion of the system with the key elements of the model and gradually increase the level of detail. The best way to make sure that the model is built in the right way is to verify each step right after the according section of the model has been programmed, because then the analyst still can remember what he did last. It is more difficult to locate the section containing error when the model becomes more complex. Therefore, the process of translating and verifying a model are closely interrelated and should be performed concurrently.

2.2.7.6 Verification

Verification is the process of ensuring that the model is free from logical errors. Verification methods include many standard techniques from software engineering, such as building and programming the model in small modules, debugging each module before putting them together, having several experts review the model, testing the model using simplified assumptions so that the output can be compared with analytical solutions, using realistic input data sets and checking for corresponding realistic outputs, and tracing through detailed logic as the simulation runs. Many simulation software packages now include animation capabilities, whereby an animated graphical representation of a model can be viewed as the simulation runs. Animation provides a means to observe how the model behaves and can help identify logical problems that are not expected to see normally. These are often symptoms of programming errors /Evans98/.

2.2.7.7 Validation

Validation is one of the most difficult problems that analyst is confronted with during a simulation project. Validation is the process of ensuring that the model is a good representation of reality /Evans98/. Furthermore, validation also aims at increasing the level of credibility in order to convince managers and other decision makers to make use of the simulation. If the validity of a model cannot be assured, any conclusions derived from the model will be of doubtful value. Validation can be viewed from many different perspectives.

Black box validation

In black box validation, both model and real system are considered as a black box. Here the inner workings of both are unknown but it is possible to observe their results. Thus, the intention is to analyse the function of both so as to decide whether their functions are sufficiently similar. The practical strategy of black box validation is simple enough. The behaviour of the real system is observed under specified conditions and the model is then run

under conditions which are as close as possible to these. If the model is valid in a black box sense, then the observations of the model should be indistinguishable from those of the real system /Pidd92/.

Historical data validation is also a part of black box validation. This approach is to compare the output of the model to historical data from the real system when the same data inputs are used /Evans98/.

White box validation

The assumption is that the internal structures of both are well understood. Clearly, this should be the case for the simulation model, as long as the modeller is in tune with his or her own creation. For the real system, this can never be wholly true but can be true enough for useful comparison to occur. White box validation most usefully takes place while the model is being constructed rather than after the event and is usually applied to the model components in turn. As far as possible, it is also applied to the interaction of the model components /Pidd92/.

Whereas the stress in black box validation is on the predictive power of the model as captured in hypothesis tests, the emphasis in white box validation is on the detailed internal workings of the model /Pidd92/.

Face validation

Face validity refers to asking experts about the simulation model or results to determine whether the model and/or the results are reasonable. This might include comparing the structure of the simulation model to the actual system, focusing attention on linkages among smaller parts of the model. Computer animation can greatly assist in this effort /Evans98/.

2.2.7.8 Experiment and analysis

The aim of experimental design is to determine alternatives that are to be simulated. A statistical design of experimental technique can be applied in this step to carry out the simulation experiments. For each system design that is simulated, decisions need to be made concerning the length of the initialisation period, the length of simulation runs, and the number of replications to be made of each run /Banks00/.

Production runs and their subsequent analysis are used to estimate measures of performance for the system. The outputs are analysed to make conclusions about the solutions of the problem studied. Based on the analysis, the analyst determines if the additional runs are needed and what design those additional experiments should follow.

2.2.7.9 Documentation and implementation

The final elements in the simulation effort are implementation and documentation. No simulation project can be considered successfully completed until its results have been understood, accepted, and used. There are two types of documentation: program and progress /Banks00/.

Program documentation is necessary for numerous reasons. It can give the understanding about how the program operates. This will build confidence in the program, so that model users and policy makers can make decisions based on the analysis. Another reason is so that model users can change parameters at will in an effort to determine the relationships between input parameters and output measures of performance, or to determine the input parameters that “optimise” some output measure of performance. Progress reports provide a chronology of work done and decisions made. This can prove to be of great value in keeping the project on course /Musselman98/.

A final report should contain clearly and concisely reported result of all the analysis. This will enable the model users and decision makers to review the final formulation, the alternative systems that were addressed, the criterion by which the alternatives were compared, the results of the experiments, and the recommended solution to the problem.

Documentation and reporting are closely linked to implementation. Careful and complete documentation of model development and operation can lengthen the model’s useful life and greatly increase the chances that recommendations based on the model will be accepted. The success of the implementation phase depends on how well the previous steps have been performed. It is also contingent upon how thoroughly the analyst has involved the ultimate model user during the entire simulation process.

2.3 SIMULATION IN QUALITY INSPECTION

There are many literatures about the application of simulation in quality area. Most of the literatures are focused on the area of quality control and statistical quality control /Aghaie97/, while the others are focused on the area of quality management systems and total quality management.

In the quality control area, simulation is used for various purposes. Some of these researches are in the quality inspection area. Palaniswami and Hassen /Palaniswami85/ created a simulation model for the analysis of a multi-product, multi-component, multi-stage (MPMCMS) manufacturing and quality system. The objective of this simulation is to provide different combinations of the quality of incoming components, quality of manufacturing and assembly blocks, and lot-by-lot (LBL) single sampling plans by attributes with rectification to evaluate final outgoing quality and the cost of the products produced by the system. Lee and Unnikrishnan /Lee98/ also developed a model for solving the problems in a multi-stage manufacturing system but focused in a different area. They developed optimal and heuristic solution methods for planning inspection activities especially in inspection allocation and assignment in a multi-stage, multi-product manufacturing environment where the total manufacturing and quality cost can be reduced without affecting the quality of the product. The performance of these methods was evaluated by simulation experiments.

In another research /Palaniswami88/, a procedure for the design and analysis of a quality control system in manufacturing is illustrated. Using this design procedure, the analyst can plan for appropriate choice of sampling plans and process capabilities in order to achieve the objectives of the manufacturing company. Moreover management could analyze and identify requirements to meet higher standards of quality.

Tannock /Tannock95/ developed a simulation model in order to evaluate inspection strategies according to process capability and cost of quality (COQ). The quality costs and Taguchi-based measure Q_{mp} were then evaluated, according to the inspection strategy selected. He also proved that the simulation method is capable of providing an insight into the comparative patterns of cost associated with control charting for variables and alternative inspection strategies /Tannock97/. The simulation results confirm that control charting of variables is much more effective than 100 percent inspection at reducing losses caused by process trends or changes in the variability when known assignable causes are applied to the data. Another simulation model was developed to investigate the cost effects of inspection and control errors /De Ruyter02/. The simulation demonstrated that inspection error had a significant effect in increasing total quality cost, with the magnitude of this increase dependent on the level of control.

Another research by Danilevich /Danilevich04/ was done in order to examine the effects of measurement errors on the reliability of random inspection and to devise effective monitoring plans. The simulation model was built and used in planning complicated inspection schemes. It aims to optimise the costs associated with organising and conducting random inspection of batches.

The effects of defect characteristics and equipment defect detection rates are studied as determinants of the optimal inspection configuration with the help of a simulation model /Delurgio97/. This research provides insights into the selection of cost effective inspection equipment and the choice of sampling plans by modelling the essential steps of integrated circuits (ICs) inspection.

Vellaisamy /Vellaisamy03/ developed an efficient algorithm in order to obtain optimal double sampling plan for certain acceptable quality level and rejectable quality level. This algorithm was explained through a suitable example for the (autoregressive moving average) ARMA(1,1) model. It leads to about 90% savings in computational timings in comparison with a crude search.

Even though, many researches have been done on quality inspection, the exhaustive investigation of inspection strategy in different planning factors with respect to quality, costs and time does not yet exist. To fill this gap in the literature, Professor Crostack, Professor Heinz and his staffs at University of Dortmund had done researches in order to investigate and evaluate the inspection strategies in manufacturing process. The comparison between existing researches and researches which are done by Crostack and Heinz are summarized in Table 2.1. A simulator named "QUINTE" was developed based on the work of Crostack and Heinz in 1997. QUINTE is a tool to evaluate inspection strategies which comprise different planning factors. The detail about this simulator will be described in the next section.

	Studied Parameters									Performance Measures		
	Inspection type	Inspection point	Inspection extent	Inspection Location and personnel	Inspection equipment	Capability of manufacturing process	Capability of assembly process	Quality of incoming material	Quality of component	Quality	Cost	Time
Research by:												
Palaniswami (1985, 1988)			X			X	X	X	X		X	
Tannock (1995, 1997)			X			X					X	
Delurgio (1997)					X						X	
Lee (1998)		X								X	X	X
De Ruyter (2002)					X						X	
Vellaisamy (2003)			X							X		
Danilevich (2004)			X		X						X	
Crostack (1999, 2004)	X	X	X	X	X	X		X		X	X	X

Table 2.1: Literatures in simulation in quality inspection

2.4 THE EXISTING SIMULATOR “QUINTE” AND “QUINTE+”

2.4.1 The QUINTE simulator

There are many general-purpose simulators on the market. Most of them focus on production and material handling systems. Some can be useful for matters which are related to quality. However, since they are not directly aimed at the quality area, so some features which are valuable to quality engineers are lacking. Therefore, a simulator called QUINTE (Qualität IN der TEilefertigung) has been developed at the University of Dortmund, Germany in the co-operation between Department of Quality Management and Department of Industrial Engineering and Applied Ergonomics. The simulator focuses on the inspection strategy and its interaction with production process. It is designed to investigate the impact of different inspection strategies on manufacturing cost, cycle time, and product quality /Crostack99/.

In contrast to general-purpose simulators, QUINTE was designed to simulate the machining as well as the inspection in a more detailed way. The flow chart of QUINTE components is shown in Figure 2.9.

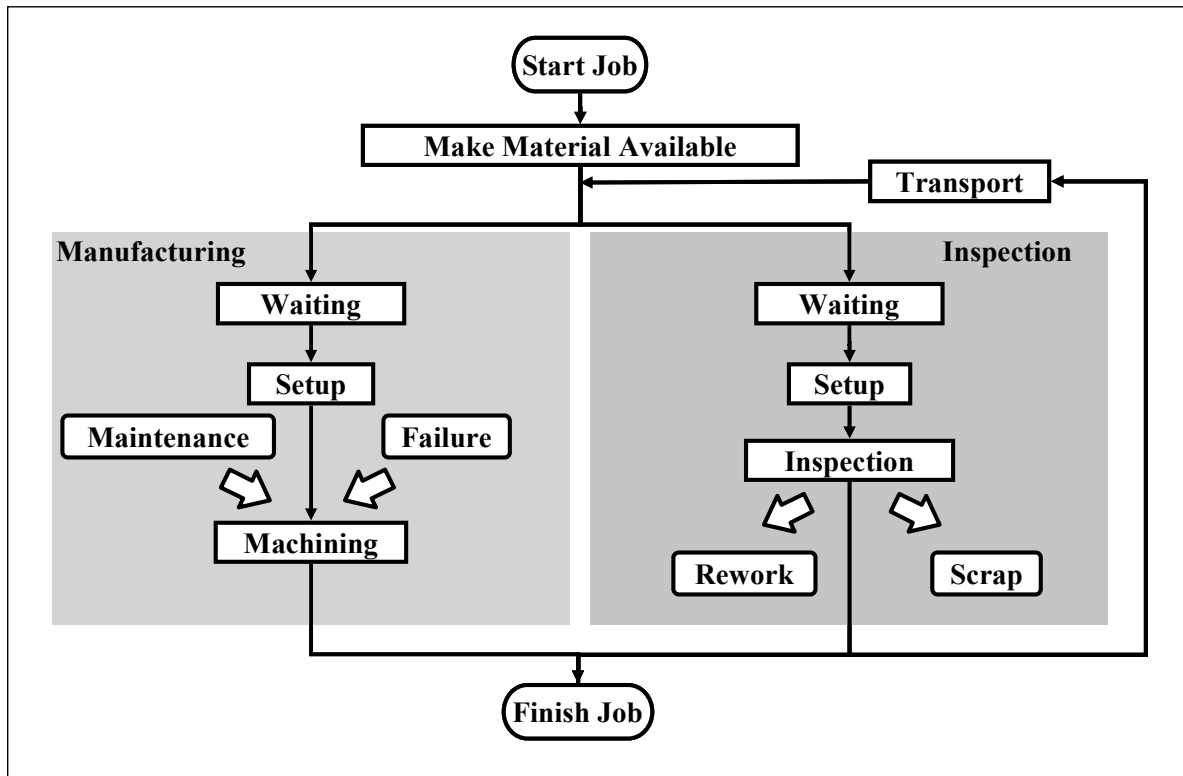


Figure 2.9: Components of QUINTE /Crostack99/

Initially, the model of the machining process capability is characterised by its own statistical distribution. The model can be represented by different distributions depending on the current process capability. For example, the model can be represented by a normal distribution with a certain standard deviation σ and mean μ . The process capability is not constant over time. The expected value can glide from its original value or the deviation can increase because of failure, wear of the tool, etc. This changed distribution can be restored or improved by setting up and maintenance.

The simulator models the disturbance of machining process in two ways. First respect is the failure. The failure of machine is randomly created as indicated by mean time to failure (MTTF). When failure occurs, the part which is still being operated by the machine can be either a scrap or its operating can be continued after the repair. The second respect is the maintenance. In this case, the maintenance starts performing when the current operating lot is finished. The machine cannot operate for a certain time because it is being maintained.

This kind of dynamic distributions can also be modelled by QUINTE. QUINTE models the actual distribution at the time of use by taken the original distribution, failures, and maintenance into account. The example of how QUINTE generates the actual distribution of quality characteristic in the form of normal distribution is shown in Figure 2.10.

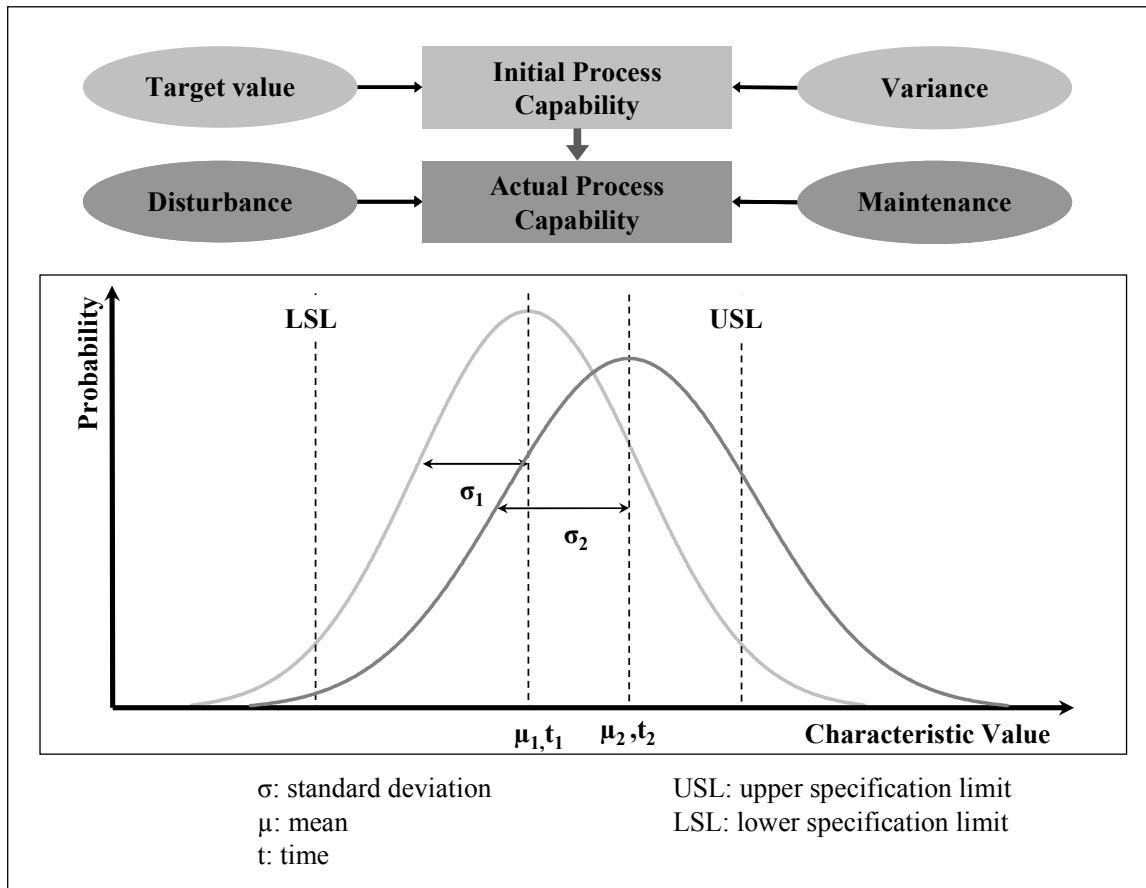


Figure 2.10: Example of how QUINTE generates the actual distribution of quality characteristic in the form of normal distribution

Then, according to the statistical model, QUINTE randomly simulates the quality characteristic value of the given process. The obtained characteristic value denotes the actual value of a characteristic of a manufactured part. Once this characteristic value is acquired, it is stored in the database and is used for the inspection simulation.

The inspection process is simulated in a similar way as the manufacturing process. Due to bias and precision, the value given by the inspection tool may differ from the true value. The capability of the inspection process is described by a statistical distribution, for example, a normal distribution. A standard deviation σ_{insp} and a mean μ_{insp} are assigned for each inspection process. In contrast to manufacturing process, the ability of inspection process is assumed to be constant over time. Therefore, the standard deviation σ_{insp} is supposed to be constant. The mean μ_{insp} is not a fixed value because the process is used to find out what value is produced. Thus, the machined characteristic value is used as a mean for the inspection process.

QUINTE generates random inspected value from the specified distribution. The inspected value will be compared with the specification limit, thus deciding whether or not the part conforms. Figure 2.11 demonstrates the example of how QUINTE simulates the quality characteristic value and the inspected value.

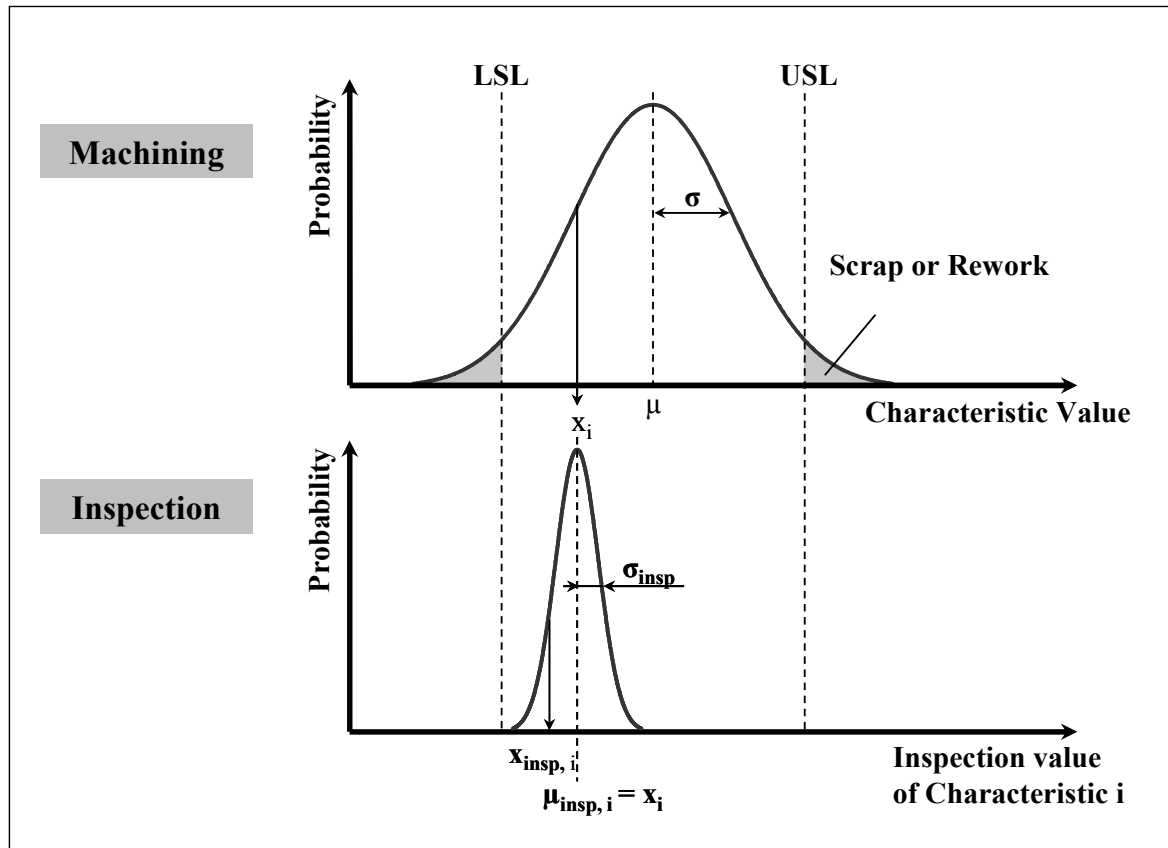


Figure 2.11: Example of how QUINTE simulates the quality characteristic value and the inspected value /Crostack99/

Furthermore, the occurrences of decision errors (type I and type II error) can also be simulated by QUINTE. Because of the variation in inspection processes, there is a possibility that a wrong decision can be made. A type I error is an error when a good part is mistakenly declared as a bad part. On the other hand, a type II error is an error when a bad part is declared as a good part. From the study of Danilevich /Danilevich04/, it shows that both types of inspection error are dependent on inspection equipment accuracy, sample size, and specification limits. Therefore, the amount of inspection errors is one main output performance which has to be considered when evaluating the inspection strategy.

After the decision is made, the part, which is declared as a conformed part, continues on its production sequence. Scraps must be sorted out and a new job must be started to replace the scraps if needed. Rework parts can be handled in two ways. The rework parts can be sent back to the preceding process or processes and the operation can be repeated. Another option is to repair the part in a separated rework area. At the end of the simulation runs, the simulation output is used in the evaluation of the inspection strategies.

QUINTE was tested in collaboration with a manufacturing company and it was possible to investigate and evaluate different inspection strategies with respect to costs, cycle times, and product quality.

2.4.2 The planning tool QUINTE+

Even though QUINTE is a valuable tool for investigate and evaluate the inspection strategy, the use of QUINTE can be time consuming and it does not guarantee the optimum solution. Therefore, after QUINTE was successfully assessed, another subsequent project /Crostack04A/ was done in order to achieve the optimum inspection strategy. The two-step procedure (Figure 2.12) for the optimisation of inspection planning, called QUINTE+, was developed. First step of the procedure is the optimisation step which contains the evolutionary algorithm that selects good alternatives out of the range of possible inspection strategies with the help of analytical cost model. In the second step, the QUINTE simulator evaluates these good strategies with respect to costs and cycle times. In both steps, the quality is represented by the capability of the processes and the failure rate caused by the interaction between manufacturing and inspection process.

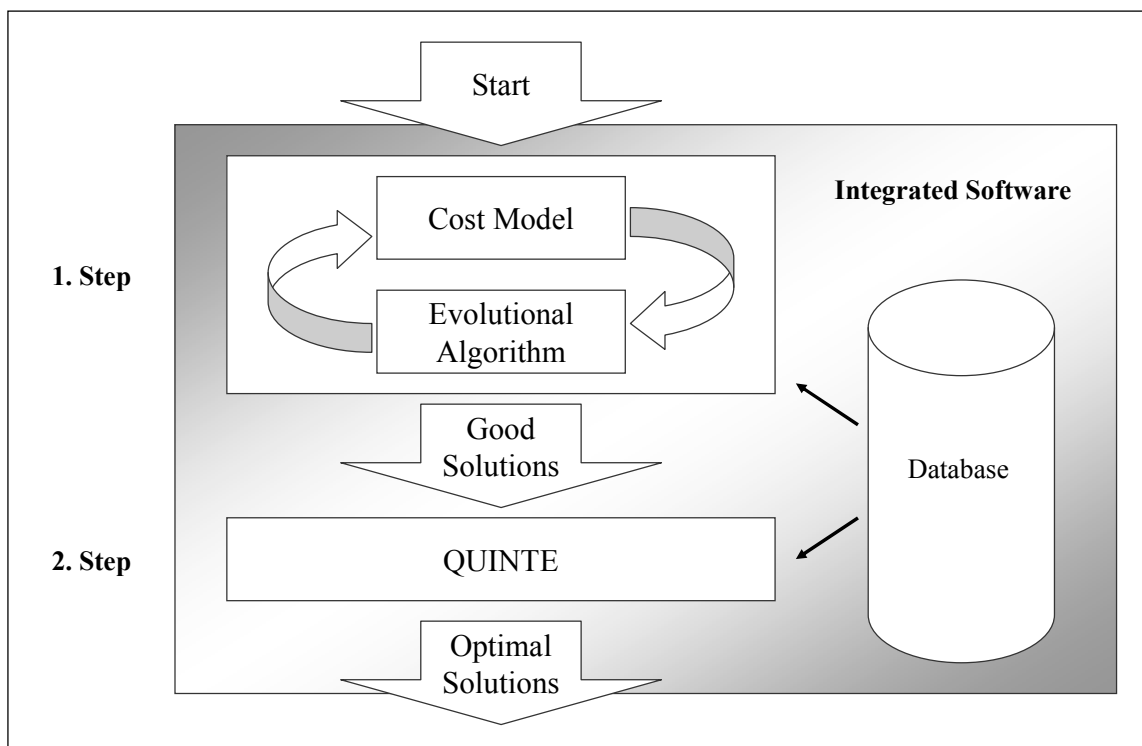


Figure 2.12: The two-step procedure of the planning tool QUINTE+ /Crostack04B/

2.4.2.1 Step one: Analytical cost model and evolutionary algorithm

In this first step, an optimisation considering the costs of every specific alternative is carried out. An analytical cost model has been developed to calculate the total costs of an inspection strategy.

The analytical cost model does not only determine the production and inspection cost. It also gives the quality cost by calculating from the ratio of scrap and rework and the average outgoing quality depending on failure rates and lot sizes. In order to calculate the ratio of defective parts, two main points are taken into account.

First of all, each process within manufacturing cannot be considered separately from the others as there are interactions between manufacturing and inspection processes. For example, the ratio of defective parts is determined by the process parameter and the variation in inspection process.

Secondly, the fact that products are not characterised only by one feature has to be considered. Therefore, to calculate the internal and external failure costs of a specific part, all of the part's quality characteristics have to be included in the calculation. For example, a part is reworked for a certain characteristic only in the case that the part is not being sorted out due to another failure.

Moreover, the probability of type I and type II error occurrences also includes in the analytical cost model. In the cost model, the quality characteristic value of manufacturing process and the inspected value are assumed to be normally distributed.

For the optimisation, an iterative procedure which related to the analytical cost model is used. An evolutionary algorithm is chosen since it can be used for a wide range of optimisation problems even for those with a high degree of complexity. This algorithm is a heuristic method and work on the principles of natural evolution.

The implementation of the algorithm includes the encoding of all possible variants of the inspection planning parameters. This contains the definition of adequate range of values for the parameters. For instance, the parameter sample size has a range from 0 to the lot size and only integers can be used.

The evolutionary algorithm starts with the values of one inspection strategy, e.g. the current situation. Then the algorithm builds possible solutions itself by randomly varying the parameters of inspection planning. The variation results from the operator's mutation, recombination, and selection of the evolutionary algorithm. The changes that lead to the better results with lower costs are kept while other parameters are changed again. The operators are adapted and enhanced to the specific optimisation problem. The solutions are evaluated and selected considering only the costs that are calculated with help of the cost model. This procedure results at least in a local optimum concerning costs.

As a result from the evolutionary algorithm, all possible alternatives of inspection strategies are reduced. Finally, only the good possible strategies are remained to be used as an input for the next step.

2.4.2.2 Step two: Simulation

In the second step of this two-step procedure, the QUINTE simulator is used to evaluate the remaining good strategies from the first step with respect to costs, cycle time, and quality. The best inspection strategy can be chosen by the users of QUINTE+ from the simulation result according to the company's goal or strategy.

In this QUINTE+ development, the simulator QUINTE itself was extended with some additional feature. The first main additional feature is the distributions for quality characteristics. Originally, QUINTE simulator can only model two distributions; normal

distribution for variable characteristic and Bernoulli distribution for attribute characteristic. Six distributions for the variable characteristics were added into QUINTE simulator. These distributions are Weibull, Uniform, Lognormal, Exponential, Gamma, and Beta distribution.

The second major additional feature is the modelling of dynamic distribution for inspection process. In the beginning, the inspection process was modelled as a static process. The capability of inspection process is assumed to be constant over time which does not mimic the reality. In reality, inspection process capability is not constant over time. The expected value can glide from its original value or the deviation can increase because of wear of the tool, etc. in the same way as in the manufacturing process. Therefore, in the enhanced version of QUINTE, the mean μ_{insp} shifts from the given machined characteristic value from manufacturing process according to time. The standard deviation σ_{insp} must as well change over time. The distribution can be restored or improved by setting up and calibration.

The investigation on the application of QUINTE+ simulator in industry was done on two pilot companies. The results show the validity of this simulator. QUINTE+ permits the enterprise to simply and economically integrate the best quality inspection strategy into manufacturing processes with consideration of quality, cost, and cycle time.

However, only models for manufacturing processes have been implemented in QUINTE so far. Therefore, the models for other processes are essential to be developed and implement in QUINTE. In this research, the application of QUINTE has been extended in the assembly process area. The basic concept of assembly process is described in the next section.

2.5 ASSEMBLY PROCESS

Most products manufactured today are too complex to be made in one piece by cutting, drilling, molding, casting, stamping, or machining. Therefore, many products are made by assembling several pieces or components. Frequently, products are built from numerous basic materials or parts, progressing through a series of assemblies into subcomponents, components, units, equipments, subsystems, and systems.

The processes that transform only one workpiece are referred in this research as manufacturing process. On the other hand, assembly operations are used to unite workpieces created by other processes. Two or more workpieces are joined, either permanently or temporarily, to create the final product being produced.

Many assembly techniques are available: mechanical, metallurgical, chemical, etc. The final products exhibit the many end-use characteristics needed by an industrial civilization: mechanical, electronic, optical, etc. /Juran74/.

Eary /Eary62/ classified the assembly processes into four general categories; heat is used to fuse metal piece together, mechanical fasteners are used to hold the assembly together, adhesives or cements may form a bond, and the components themselves maybe squeezed or formed to accomplish a joint.

In comparison with manufacturing processes, most assembly processes are reversible, i.e. faults can often be corrected by dismantling and correct reassembly. Temporary assembly is

achieved with mechanical fastener such as screws, nuts and bolts, clips and studs. Press fitting of parts can be a temporary assembly operation. However, not all assemblies can be reversed. Disassembling of the product would generally require damaging its components. Permanent assemblies are made by welding, brazing, soldering, riveting, and staking operations. The shapes and sizes of products or workpieces created by assembly operations are almost unlimited.

In any cases, the reworked assemblies are frequently less satisfactory in overall quality than “right first time” builds. Apart from this factor, reworking is costly, frustrating and time-wasting /Parry73/. Therefore, a proper inspection planning is necessary.

2.5.1 Assembly characteristics and inspection technology

In order to obtain the final product which serves the needs of the user, the assembly job should be carefully analysed to identify the characteristics that are needed to be controlled. These characteristics must be defined in measurable terms or in other ways which permit objective appraisal against a standard. There should also be an allowable tolerance to take care of normal processing and material variations. The classification of assembly characteristics and the inspection technology are explained in the following /Juran88/.

2.5.1.1 Measurable characteristics (Variable)

At first, units of measure were in terms of parts of the human body. With the expansion of commerce, and especially of international commerce, the metrologists evolved systems of international units of measure, the chief systems being the metric and the English. More recently there has been evolved a fully coherent international system, the Systèm International d’Unités (SI).

The examples of inspection technology, which are illustrated with respect to the measurement of length, are electronic measurement, pneumatic measurement, and optical measurement.

2.5.1.2 Non-measurable characteristics (Attribute)

For many characteristics there are as yet no agreed units of measure. Nevertheless, useful evaluations can be made of such characteristics by sensor testing or instrument testing.

An example of instrument testing is the non-destructive testing or NDT. It is used to detect flaws in materials and components as well as to measure physical properties such as dimensions, hardness, conductivity, composition, and magnetic and elastic constants. The test is done without impairing the subsequent usefulness of the product.

2.5.2 Sources of variation

The above assembly characteristics can be varied from the expected values or expected quality depending on sources of variation. There are three main sources of variation which must be accounted for in mechanical assemblies /Drake99/.

- Dimensional variations (lengths and angles)
- Geometric form and feature variations (position, roundness, angularity, etc.)
- Kinematic variations (small adjustments between mating parts)

Dimensional and form variations are the result of variations in the manufacturing processes or raw materials used in production. Kinematic variations occur at assembly time, whenever small adjustments between mating parts are required to accommodate dimensional or form variations. In this research, all three sources of variation are taken into account in a complete assembly model in order to assure realistic and accurate results.

2.6 SIMULATION AND ASSEMBLY PROCESS

Most of the simulation researches in assembly processes or assembly systems are on, for example, assembly process design and planning, inventory or work-in-process (WIP) problems, scheduling problem, workforce management, work allocation or line balancing problems, and efficiency of the process.

The literature on quality control in assembly processes or assembly systems with the aid of computer simulation are very limited. One of the literatures is the research by Leung /Leung96/. Leung investigated and compared between online and offline inspection strategies and repair strategies. This research is related to the determination of inspection point and inspection location in the inspection planning. A discrete event simulation model was built for the study and the factorial experiments were carried out to analyse the performance of the assembly system. The result showed that the offline repair strategy appears to perform better when the defect percentage of assemblies increases. Leung recommended the design engineers to consider using online repair strategy when the defective percentage is at low level. The result also proved that the number of repair stations can have a direct impact on the efficiency of the system. However, additional inspection and repair stations installed may potentially improve the quality of the products.

In the project of Boër /Boër03/, existing basic software for discrete simulation was used to implement a detailed model of the system in terms of both layout and logic control rules which includes the quality control cell. And it is shown from this research that a flexible and modular assembly system for complex products can be designed, developed, and implemented with the aid of computer aided simulation techniques.

Zhao /Zhao03/ developed a model which can evaluate the product assembly quality by calculating the assembly efficiency and the ratio of the part function value to its assembly difficulty. This model has been integrated into CAAPP (Computer Aided Assembly Process Planning).

It is clearly shown that the literature on investigating the complete inspection strategy in assembly process is still lacking. Therefore, this research aims to develop a simulator which

can be used to investigate and evaluate the inspection strategies which involve different planning factors with respect to quality, costs and time in assembly process. It is a subsequent research from QUINTE project since QUINTE can only evaluate inspection strategies in manufacturing process.

2.7 TOLERANCE PLANNING

2.7.1 Tolerances

Tolerance is defined by ASME Y14.5M-1994 /ASME98/ as the total amount a specific dimension is permitted to vary. The tolerance is the difference between the maximum and minimum limits.

Tolerances are required in the production because it is impossible to produce anything to exact specification due to the sources of variation. It is also a language for communicating engineering design specification /Drake99/.

2.7.1.1 Importance of tolerances

As introduced previously, tolerances make it possible for one producer to use components which are produced by other producers. However, the requirements from the engineering and manufacturing sides, which are shown in Figure 2.13, are not in the parallel direction. Engineers like tight tolerances to assure fit and function of their designs, however, tight tolerances can result in excessive process costs. Manufacturers prefer loose tolerances which make parts easier and less expensive to produce. On the other hand, loose tolerances may lead to increased waste and assembly problem. Therefore, the specification of tolerance limits on each dimension and feature of engineering drawings becomes a critical link between engineering and manufacturing. Tolerances must be planned carefully in order to provide a common meeting ground where competing requirements can be solved with an optimum cost and time.

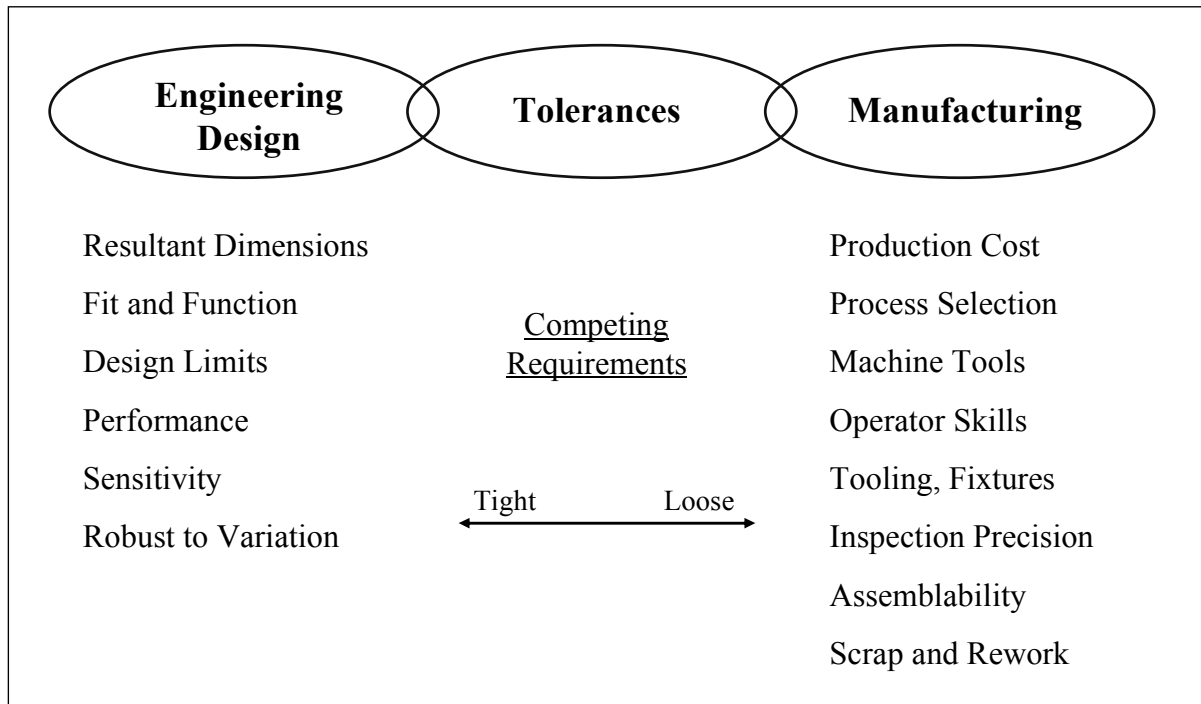


Figure 2.13: Tolerance – A critical link between design and manufacturing /Chase91/

2.7.1.2 Classification of tolerances

Tolerances can be classified into three main types according to its quality characteristic /Chase97/.

- Dimensional tolerances: These tolerances limit component size variations.
- Geometric tolerances: Geometric tolerance /ASME98/ is defined as the general term applied to the category of tolerances used to control form, profile, orientation, location, and runout. They are added to further limit the form, location or orientation of individual part features.
- Assembly tolerances: The specifications are added to limit the accumulation of variation in assemblies of parts to a level dictated by performance requirements.

The dimensional tolerances and geometric tolerances can be called as process tolerances since they are the variations in specification that occur as a result of the manufacturing process of individual components. This type of tolerance is dependent on tool and machine types, the type of process, and the material being worked on. Operator errors, incorrect machine setup, and tool wear are all contributors to process tolerances.

Assembly tolerances are the result of parts of varying shape and size being put together to make the finished product. The variations or errors of manufacturing processes can build up and each contributes to the overall assembly dimension, affecting its acceptance or rejection at the end of the production stage. This phenomenon is referred to in the literature as tolerance stack up /Ashiagbor98/. Additionally, the ways in which the assembly is performed will affect the critical assembly dimension.

The tolerances for quality characteristic, which are described above, can be broke down into three types as shown in Figure 2.14.

- Functional tolerances: They are derived from threshold of the functional performance. They represent the limits where the characteristic can fulfil or cannot fulfil its function.
- External tolerances: These tolerances represent the acceptance of the client which in line with the inspection at the customer's site such as the specifications of the incoming inspection at customer's site.
- Internal tolerance: They are the limits which are used within the company. They are the assessment basis for the acceptance or rejection of the inspected part.

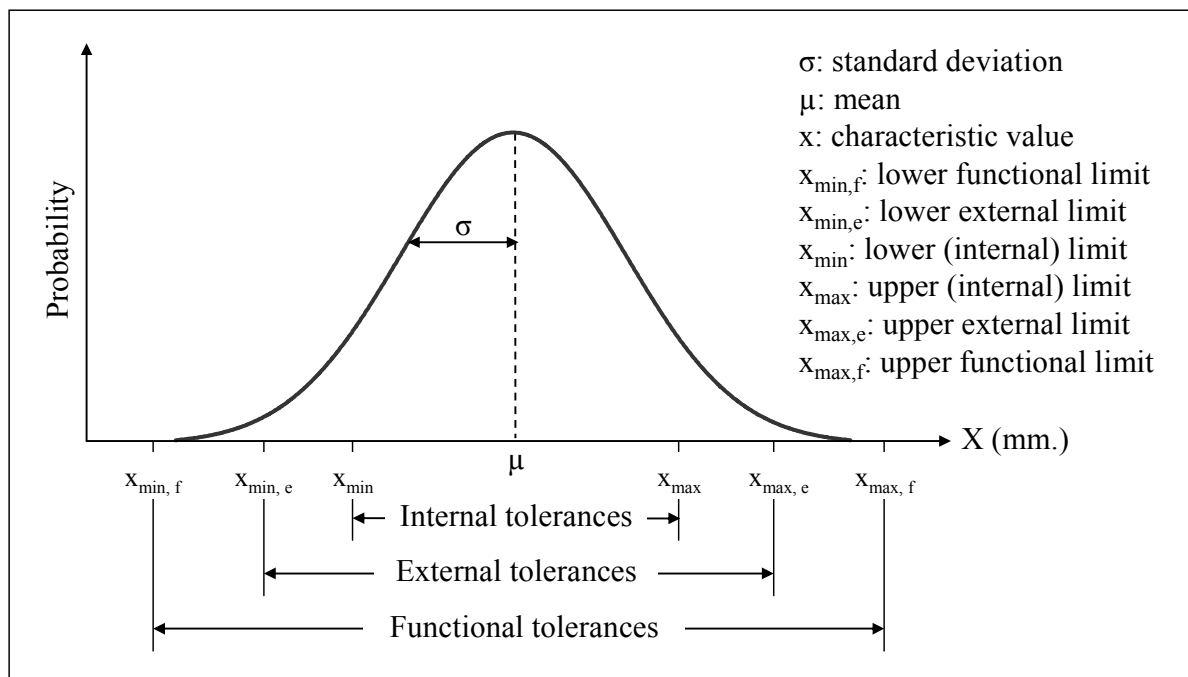


Figure 2.14: Example of functional, external, and internal tolerances /Nürnberg99/

2.7.2 Quality problem related to tolerancing

It is often found that the distribution, which represents quality characteristic values of manufactured or assembled product, changes in line with time. The mean or standard deviation of the distribution can shift which resulting in large numbers of rejects at one or the other specification limit. This can be caused by tooling bias, setup error, shrinkage of molded or cast parts, or other factors.

Considering this distribution shift, Nürnberg /Nürnberg99/ has done a research to create a systematic way to design the external and internal tolerances for critical characteristics with the help of simulation. Quality, cost, and time are considered in his tolerance design. He applied the concept of risk-based tolerancing approach into his research. The total risk includes internal risk such as rework or scrap, external risk such as customer's claim or

inspection cost at customer's site, and risk in terms of the monetary loss according to Taguchi's philosophy. The Taguchi's quality loss is clarified in section 2.7.3.2.

When the tolerances cannot be adjusted or it is too costly to adjust the tolerance, the adjustments on process should be done instead to eliminate or reduce this quality problem. There are three methods which are recommended by Chase /Chase99/. These methods, which are used to reduce the number of rejected parts, are described in the following section and illustrated in Figure 2.15.

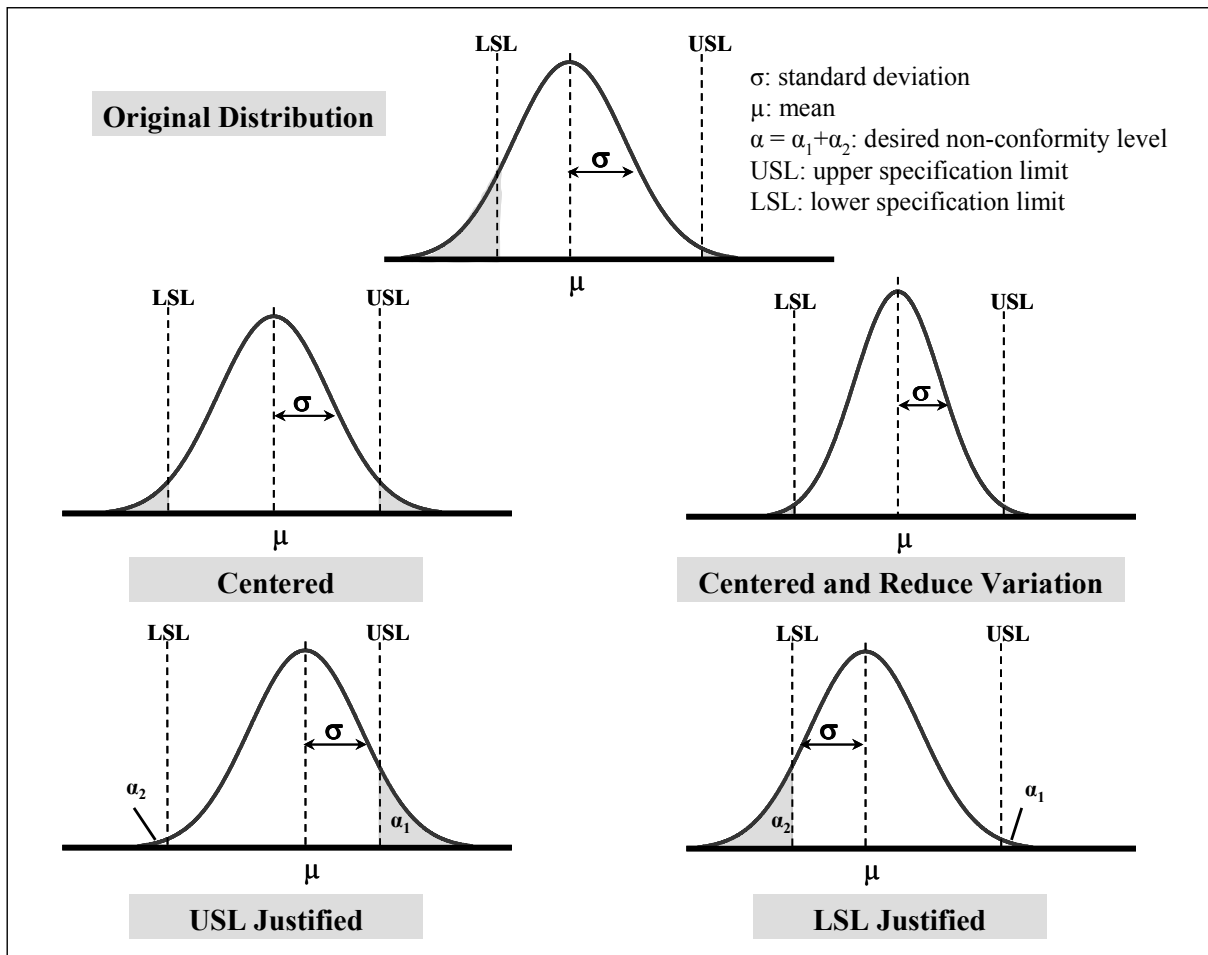


Figure 2.15: Methods for process adjustments – Example

2.7.2.1 Centering the mean of the distribution

This first method can be used for the characteristic that has two-sided tolerance limits and these limits are equally critical.

Centering the mean puts the greatest distance between tolerance limits and the mean, thus minimizing the number of rejects for a given process distribution. The adjustment can be done on the certain part to improve its quality or it can also be done on one or more components in order to obtain the centered distribution of assembly process.

2.7.2.2 Upper or lower limit justification of the mean

The adjustment can also be made to the process to shift the distribution towards either the upper or lower specification limit until the desired quality level is reached. This may be desirable if there is only one specification limit or if one of the two specification limits is more important than the other. The distribution is simply adjusted without changing its deviation as with centering method.

In upper specification limit justification, the center of the distribution is shifted such that the $+Z\sigma$ limit matches with the upper specification limit, where σ is the standard deviation of the distribution and Z is the desired quality level expressed in standard deviations. For example, if the desired quality level (Z) is 3, the process gives around 2700 defects per million parts produced. Likewise, in lower specification limit justification, the distribution is adjusted such that the $-Z\sigma$ limit matches with the lower specification limit.

2.7.2.3 Variance adjustment

If the mean has been centered and the reject rate is still too high because the spread of the distribution is too broad, it will be necessary to improve the process capability in order to reduce the standard deviation of the process distribution. For the assembly process, it is also possible to tighten the tolerances on one or more assembly component dimensions in order to reduce the standard deviation of the assembly.

2.7.3 Tolerance analysis and tolerance allocation

The matter of tolerance planning for a single-component product is not difficult. The proper tolerance can be determined from the process distribution for the component. However, planning tolerances for a finished product consists of many components created by different process is not an easy task. The planner has to determine which combination of component tolerances is best. There are two main problems in tolerance planning, which are tolerance analysis and tolerance allocation.

2.7.3.1 Tolerance analysis

Tolerance analysis is a quantitative tool for predicting the effects of manufacturing variation accumulation on performance and cost in assemblies /Drake99/. Tolerance analysis or tolerance control in some literature /Ashiagbor98/ can be done at design phase or production phase in order to improve the tolerance design. In design phase, it enables designs with unrealistic critical dimension tolerances to be detected early in the production process, thus saving the time and expense of actually going to production before this is realized /Ashiagbor98/. It can also be performed after the parts are in production. The tolerances can be systematically selected throughout an assembly to assure that design requirement will be met with high process yield and reduced costs /Chase91/.

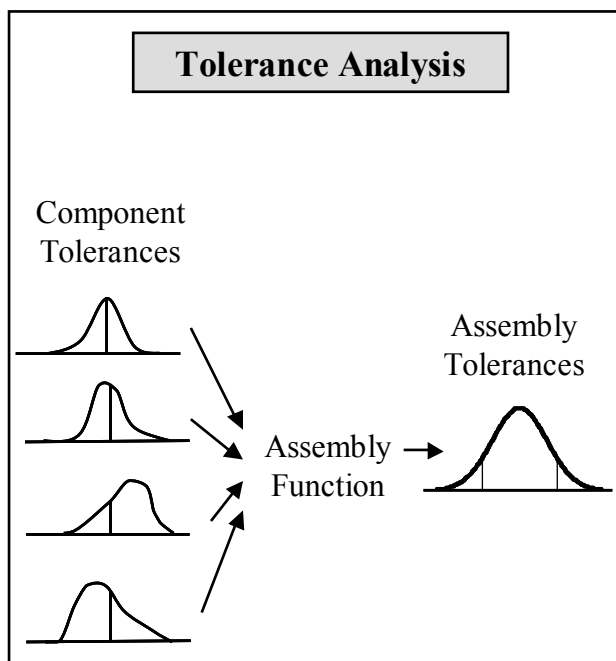


Figure 2.16: Tolerance analysis /Chase99/

In tolerance analysis, the component tolerances are all known or specified and the resulting assembly variation is calculated. The assembly yield or assembly quality level is unknown. It is calculated by summing the component tolerances to determine the assembly variation. The upper and lower specification limits is then applied to the calculated assembly distribution /Chase99/.

In order to predict the effects of manufacturing variation in assemblies, a model of tolerance accumulation should be created. There are number of models, which were surveyed by Chase /Chase91/, exist with varying levels of sophistication as shown in Figure 2.17.

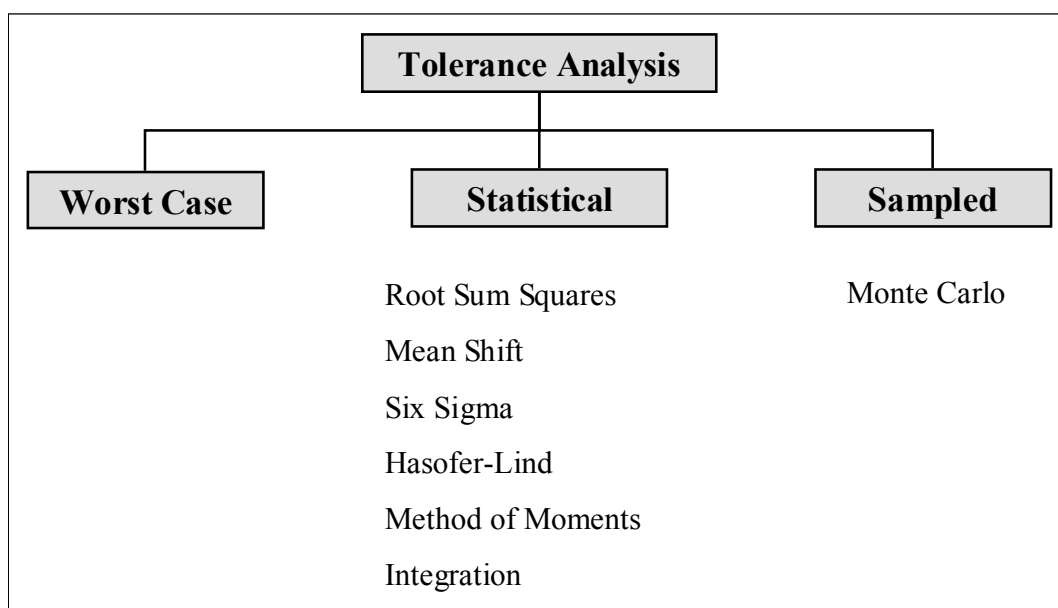


Figure 2.17: Models of tolerance accumulation /Chase91/

Worst case, root sum squares, mean shift, and six sigma are commonly linearised model. The linearised models for tolerance accumulation in an assembly assume that the sensitivity is constant over the tolerance limits. That is, if the assembly function was evaluated by varying one parameter over its tolerance range, the slope of the function would be nearly constant. This is usually a reasonable assumption, when the tolerances are very small compared to the nominal dimensions or when there is a large enough number of components to mask the effects.

In a highly non-linear assembly, the sensitivity may not be symmetric over this range and the distribution of the assembly resultant will be skewed or asymmetric. This can happen even though all of the component distributions are symmetric. A linearised model, however, will always yield a symmetric resultant from symmetric inputs.

Analysis methods, which can treat non-linear effects, are Hasofer-Lind, Method of moments, Integration, and Monte Carlo simulation. The comparison of tolerance analysis methods, which was done by Chase /Chase91/ is summarised in Table 2.2.

Analysis Method	Assembly Model		Distributions	
	Linearised	Non-linear	Normal	Non-normal
Worst Case	X	X	NA	NA
Root Sum Square	X		X	
Mean Shift	X		X	
Six Sigma	X		X	
Hasofer-Lind		X	X	
Method of Moments		X	X	X
Integration		X	X	X
Monte Carlo	X	X	X	X

Table 2.2: Comparison of the tolerance analysis methods

In the following, only Monte Carlo simulation method is described in detail since it is related to this research.

Monte Carlo simulation is a powerful tool for tolerance analysis of mechanical assemblies, especially for both non-linear assembly function and non-normal distributions. It is based on the use of a random number generator to simulate the effects of manufacturing variations on assemblies.

The steps in Monte Carlo simulation method /Chase91/ are shown in Figure 2.18.

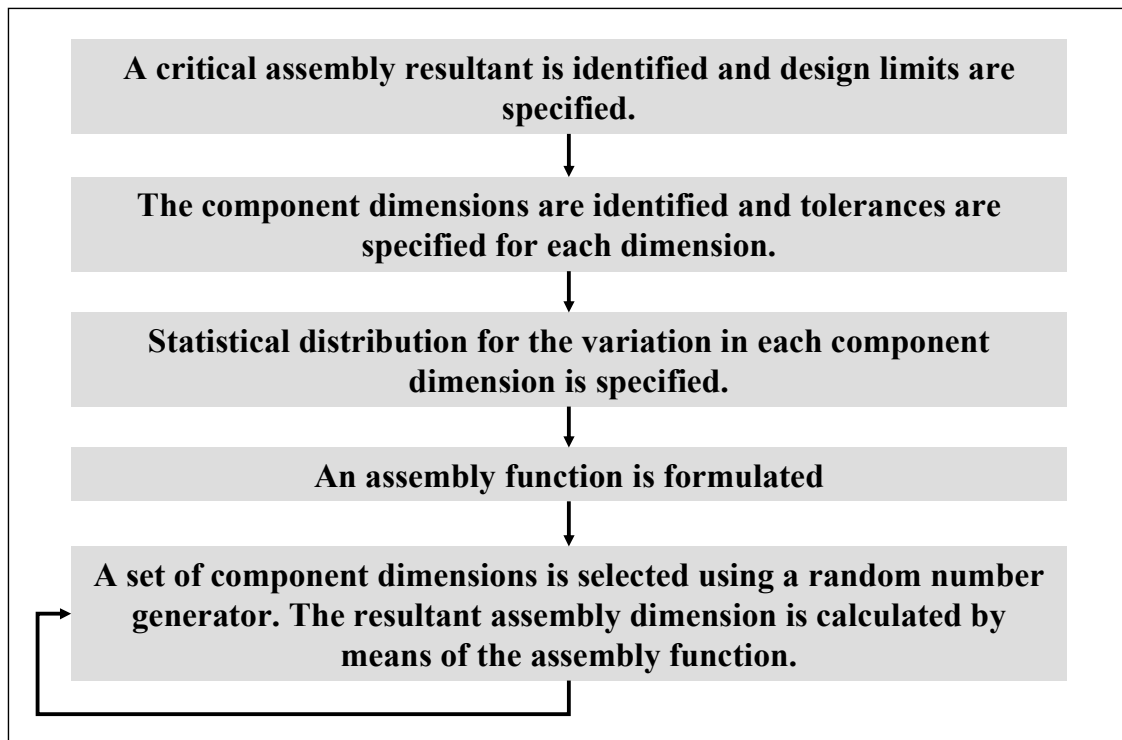


Figure 2.18: Steps in Monte Carlo simulation

The resultant assembly dimension from the last step is compared to the assembly limits to determine if it is within specifications. And this step is repeated until a sufficient number of assemblies have been simulated to plot a histogram and estimate the percent of assemblies that would be rejected based on the specified tolerances. Then a distribution can be fit to the histogram and this distribution function can be used to calculate the percent rejects.

The biggest disadvantage of the Monte Carlo method is that it requires large samples to achieve reasonable accuracy. However, this disadvantage is lessened by the power of the computer nowadays.

2.7.3.2 Tolerance allocation

Tolerance allocation, which can be called as tolerance propagation or tolerance design, determines the tolerances to be assigned to those dimensions contributing to a functional or sum dimension such that production cost is minimised /Ashiagbor98/. It is a design function which is performed early in the product development cycle before any parts have been produced or tooling ordered. In tolerance allocation problem, the assembly tolerance is known from design requirements, whereas the magnitudes of the component tolerances to meet these requirements are unknown. The available assembly tolerance must be distributed or allocated among the components in some rational way /Chase99/. The component tolerances must be set to assure that the resulting assembly yield or quality level meets the specified design requirement.

Tolerance allocation allows optimal or near optimal allocation of tolerances to those dimensions that contribute to the critical dimension given that its tolerance has been specified by designer in order to reduce instances of scrap and rework which all increase manufacturing cost and product lead times /Ashiagbor98/. The following figure illustrates the design procedure of tolerance allocation.

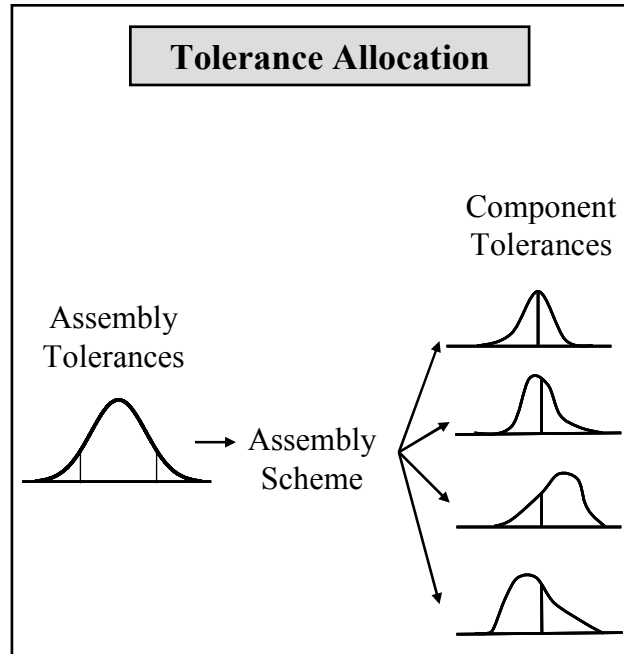


Figure 2.19: Tolerance allocation /Chase90/

As shown in Figure 2.19, tolerance allocation involves three steps /Chase91/ which are:

- Deciding what tolerance limits to place on the critical clearances and fits for an assembly, based on performance requirements.
- Creating an assembly model to identify which dimensions contribute to the final assembly dimensions.
- Deciding how much of the assembly tolerance to assign to each of the contributing components in the assembly.

Tolerance design is often performed by repeated application of tolerance analysis, using trial values of the component tolerances. However, a number of algorithms have been proposed for assigning tolerances on a rational basis, without resorting to trial and error. Several algorithms which were surveyed by Chase /Chase91/ are listed in Figure 2.20.

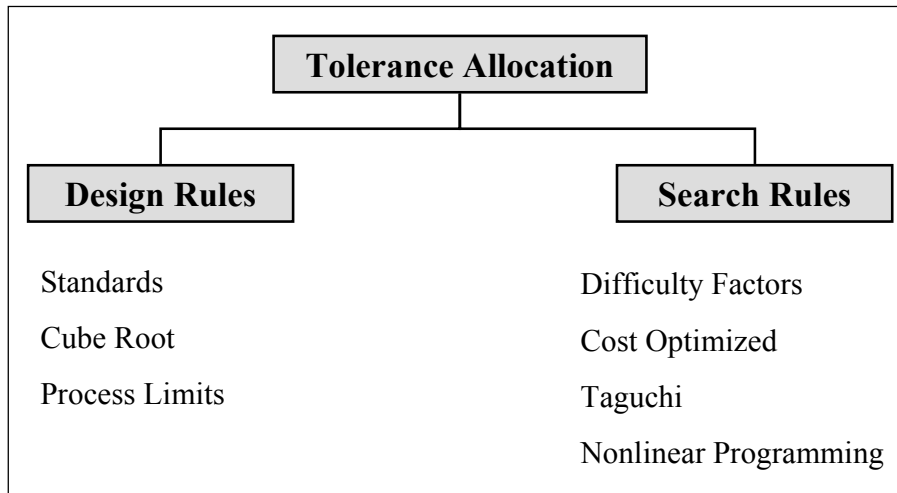


Figure 2.20: Tolerance allocation methods /Chase91/

Most of the algorithms, which are used to solve tolerance allocation problem, are done analytically. However, simulation method can also be applied together with other algorithms, such as in the research of Jeang /Jeang99/. He applied simulation method to obtain experimental data and then he used response surface methodology (RSM) to optimise and analyse computer results in order to determine the optimal tolerance design in an assembly.

The procedure which Jeang used to develop an optimal tolerance design is summarised in Figure 2.21.

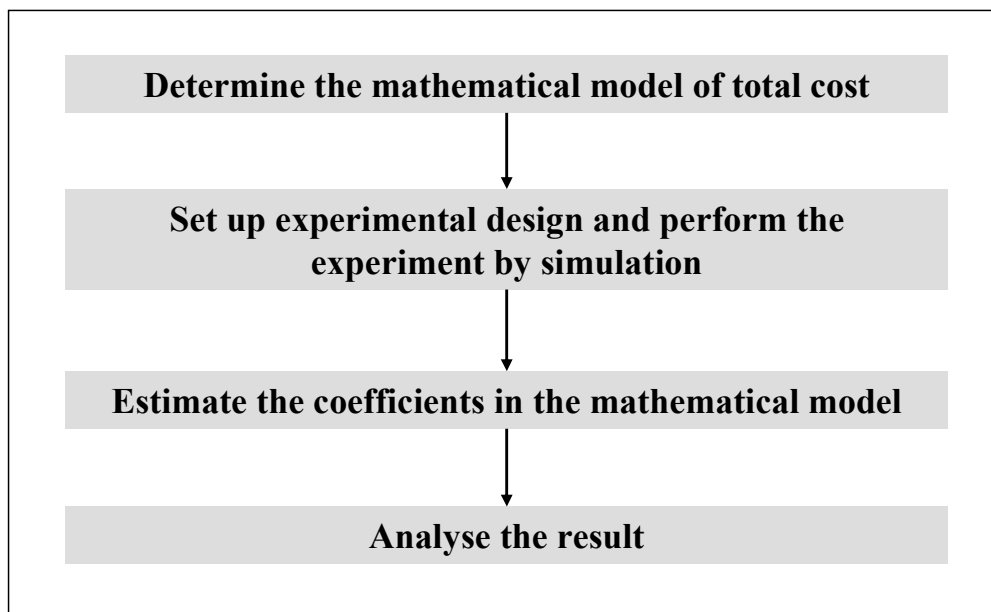


Figure 2.21: An example of the procedure for solving tolerance allocation problem

In the beginning Jeang determined the mathematical model of total cost by considering tolerance-cost function and Taguchi's quality loss function. Before describing the next step of Jeang's procedure, the background information regarding tolerance-cost function and quality loss function is introduced for a better understanding.

Tolerance-cost function is concerned in the solving of tolerance allocation problem since each component tolerance may have a different manufacturing cost associated with it due to part complexity or process differences. Manufacturing cost usually increases as the tolerance of the quality characteristics is reduced, due to the need for more refined and precise operations. On the other hand, large tolerances are less costly to achieve as they require less precise manufacturing processes, but they usually result in poor performance, premature wear and part rejection. The typical tolerance-cost function (Figure 2.22) is basically a reciprocal function which estimates the decrease in cost for an increase in tolerance /Chase90/.

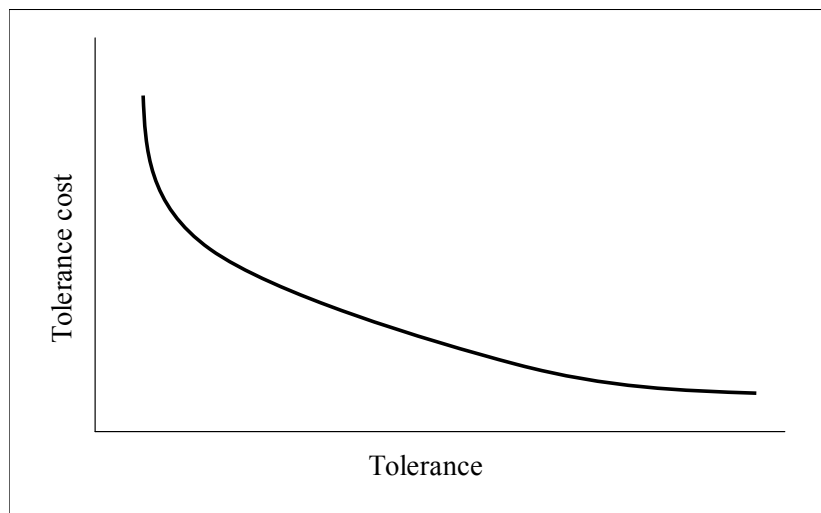


Figure 2.22: Typical tolerance-cost function /Chase90/

Taguchi's quality loss function is developed by Dr. Genichi Taguchi. He understood and quantified the fact that any deviation from the nominal will cause a quantifiable cost or loss /Taguchi70/. Most western management thinking today still believes that loss occurs only when a specification has been violated, which usually results in scrap or rework. The truth is that any design works best when all elements are at their target value and the deviations from standard are losses. These losses are in performance, customer satisfaction, and supplier and manufacturing efficiency. These losses are real and can be quantified in terms of money /Drake99/.

The loss function is a quadratic expression for measuring the cost of the average value versus the target value and the variability of product characteristics in terms of monetary loss due to product failure in the eyes of the consumers. The loss function is illustrated in Figure 2.23.

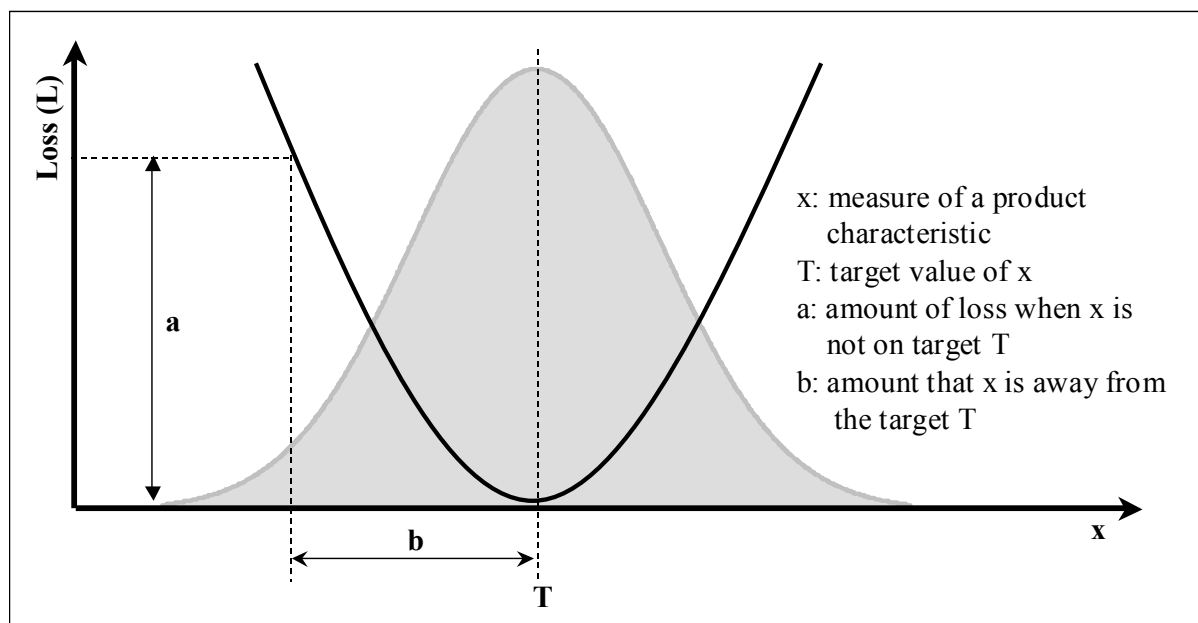


Figure 2.23: Taguchi's loss function and a normal distribution /Drake99/

The simple case for one value of x , the loss is /Taguchi89/:

$$L(x) = k(x-T)^2, \text{ where } k = \text{loss coefficient} = a/b^2 \quad (2.1)$$

This simple quadratic equation is a good model for estimating the cost of not being on target.

The more general case can be expressed using knowledge of how the product characteristic (x) varies. The following model gives the average loss of a sample set. It assumes a normal distribution, which is symmetrical about the average \bar{x} .

$$L = k[(\bar{x}-T)^2 + s^2], \text{ where } s = \text{the standard deviation of the sample of } x\text{'s} \quad (2.2)$$

The calculation for the loss in practice can start from calculating the loss coefficient (k) at the upper or lower specification limit. For example, a company produces a part that has a target hole diameter of 0.5" and the tolerance of +0.05". Failure cost per part is \$0.45 /Smith07/. Then the loss coefficient can be calculated from equation 2.1.

$$L = k(x-T)^2 \text{ or } k = a/b^2$$

$$k = 0.45/(0.55-0.5)^2 = 18000$$

The average loss per part can be calculated from the measured characteristic of the sampled products by equation 2.2. In the example case, the measured hole diameter of 30 sampled products are shown below:

0.459	0.478	0.495	0.501	0.511	0.527
0.462	0.483	0.495	0.501	0.516	0.532
0.467	0.489	0.495	0.502	0.521	0.532
0.474	0.491	0.498	0.505	0.524	0.533
0.476	0.492	0.500	0.509	0.527	0.536

$$L = k[(\bar{x} - T)^2 + s^2]$$

$$L = 18000[(0.501 - 0.5)^2 + 0.022^2] = \$8.73$$

The loss of total 30 parts produced is \$261.90.

After Jeang determined the mathematical model of total cost, he set up the experimental design. And this is where the simulation came in. The simulation is used to perform the experiments. The experimental results from simulation will then be used to estimate the coefficients in mathematical model. The last stage is to analyse the result. The result gives the optimal tolerance values and also the critical components of an assembly.

Another research that is worth mentioning is the work of Merget /Merget04/. He developed a method to identify the components' tolerances which give the optimal costs. The idea behind his research is that, in order to reduce the production and inspection costs, the simple and low-cost components should have a narrow tolerance while the hard-to-produce and high-cost components should have the wide tolerance. The example of his idea is shown in Figure 2.24. The example shows that the new tolerances are better than the old tolerances when $\Delta C_G > \Delta C_S + \Delta C_B$ based on total cost perspective. Unlike Jeang's approach, Merget estimated the costs and done the experiments manually. The tolerance-cost curve for each characteristic was built in 3 estimation schemes; optimistic, neutral, and pessimistic. As stated in Merget's outlook, the methods other than manual estimation could have been used in the cost estimation in order to deliver the more accurate tolerance-cost curves. Simulation is one of the potential methods to play a significant role in this part.

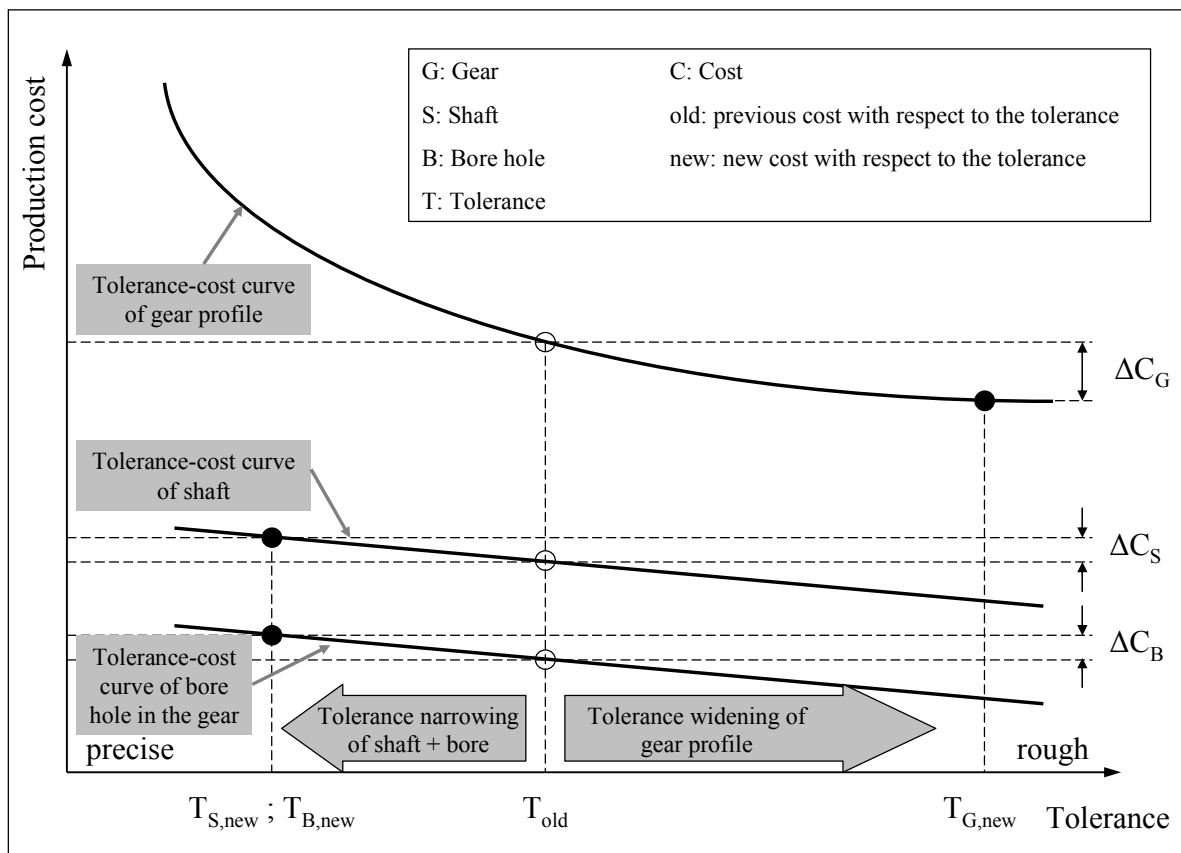


Figure 2.24: Example of core idea in tolerancing by Merget /Merget04/

This section has shown that simulation can be used as a helping tool in tolerance planning and tolerancing problem solving. The simulator, which is the outcome of this dissertation, can help as well in tolerance planning and tolerancing problem solving. It provides the opportunity to analyse both individual component or part and the whole assembly by taken quality, cost, and time into account. In order to improve overall quality, cost, and time in the production, only tolerance adjustment may not give a satisfactory improvement. The improvement can be excelled when tolerance adjustment is done together with implementing a good inspection strategy. With this simulator, the tolerance analysis can be done at the same time as inspection planning. This leads to cost reduction and shorter planning time.

3. SIXSIGMA – A NEW SIMULATOR

The SixSigma simulator, which leads to assembly process improvement, is comprehensively described here. The chapter starts with the concept of the simulator. It includes the level of details and all assumptions that are made in constructing this simulator.

The simulator was built in the form of template in Arena® simulation software. The in-depth explanation on the template is comprised in this chapter. The user's instruction plus the logic behind all ten modules in SixSigma template are also clarified. The modelling example is shown in the third section of this chapter. The verification and validation of SixSigma template is presented as a final point.

3.1 CONCEPT OF THE SIMULATOR

In order to develop a simulator, the concept of the simulator has to be created. The simulator creates job order from the specified order sequence or it can randomly create the job order from the specified arrival rate. The order should consist of the part and amount to be produced.

Once the job order is created into the system, the parts will be created according to part type and amount of parts in the order. These parts can be transported to one of the three processes. There are three main processes in SixSigma simulator; manufacturing process, assembly process, and inspection process. These processes will be discussed individually later on in this section. After the completion of the process, the part will go to the next production sequence either the next manufacturing process, assembly process, or inspection process. When the product is completed, all the required data will be stored and the product will exit the system.

The overall concept of SixSigma simulator in graphic form is presented in Figure 3.1.

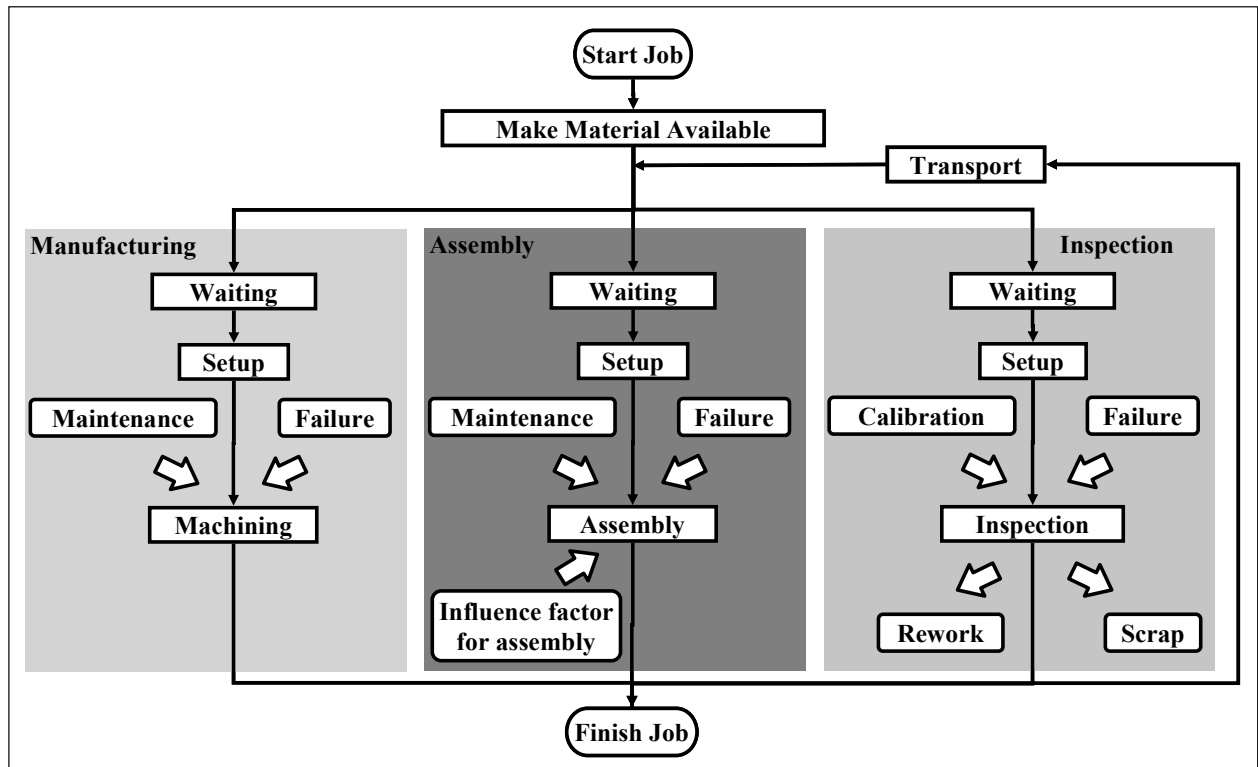


Figure 3.1: Components of SixSigma simulator

3.1.1 Level of detail and assumptions

Since it is not possible to develop a simulator that covers all the aspects in reality with the time constraint, some assumptions have to be done. The followings describe the level of detail and assumptions which are used in this simulator.

3.1.1.1 Level of detail

The followings describe items, which are included and not included in the simulator.

- Sources of raw material such as different suppliers are not taken into consideration.
- Manufacturing and assembly industries are the only main attention of this simulator.
- Failure and maintenance of each machine are modelled.

3.1.1.2 Assumptions

The following list summarizes the assumptions on which the simulator is based.

- Quality of incoming raw material is assumed to be 100% conforming and the raw material is always available.
- Queues in front of each machine have unlimited capacity.
- Human error, which is caused by the operators, is included in process capability.

- Transportation is possible to describe in terms of “travelling time”.
- Holding costs are known and it can be used to calculate for value added cost, non-value added cost, waiting cost, transportation cost, and other costs.

3.1.2 Manufacturing process

The concept of manufacturing process in SixSigma simulator is based on the manufacturing process in QUINTE simulator. A part enters a manufacturing process and goes first to the queue in front of the machine. When the machine is free for the part, it will be set up and then the part will be seized into the machine. After the machining process, the quality characteristic is assigned to the part depending on the model of the machining process capability.

The model of the machining process capability is characterised by its own statistical distribution. The simulator currently allows specification of the following distribution types: Bernoulli, beta, Erlang, exponential, gamma, lognormal, normal, Poisson, triangular, uniform, and Weibull. This model is a dynamic model. The parameters for the specified distribution are not constant over time. The model can get worse because of several reasons such as failure and wear of tool. However, it can be restored or improved by setting up and maintenance. From this dynamic model, the simulator generates a random number belonging to the specified distribution at the time of simulation. This random number is defined as the actual quality characteristic of the manufactured part. The quality characteristic is stored as an attribute of the part.

The failures of machines are created at a certain point in simulation as indicated by mean time to failure (MTTF) or by number of units that already machined and machine down time. When failure occurs, the part, which is still being operated by the machine, will be stopped and its operating can be continued after the repair. The simulator simulates maintenance according to maintenance interval either in time interval or machined unit interval and maintenance duration. The maintenance starts performing when the current operating part is finished and the machine cannot operate during the maintenance.

After the machined part acquires the quality characteristic value, it will continue to the next production process either the next manufacturing process, assembly process, or inspection process.

3.1.3 Assembly process

The quality characteristics from assembly process can be classified into two main categories: attribute or variable characteristic. The attribute characteristics can be represented by Bernoulli distribution. The probability of conforming characteristic is denoted by p and the probability of non-conforming characteristic is denoted by $(1-p)$. On the other hand, variable characteristics can be represented by the other ten statistical distributions in the same way as in manufacturing process.

The accuracy of some assemblies is determined primarily by the accuracies of the individual components to be assembled. In other words, the closeness of fits between components

determines the assembly tolerances. In other assembly work, the assembly tolerances are determined by the accuracy of the tooling or fixtures. Sometimes the assembly operation used will directly cause variations in the assembled components, for example, the heat applied during assembly or the squeezing forces. Some assembly operations tend to hold closer tolerances such as press fitting and brazing.

Since the quality of the components from manufacturing process affects the quality of the assemblies significantly, these interactions between manufacturing and assembly process are necessary to be included in the simulator. The concept of how to include this effect in the model is discussed in section 3.1.3.1.

3.1.3.1 Modelling quality effects of manufacturing processes on assembly process

The model concept can be divided into two parts. The first part is when the characteristics of all components are conforming. The simulator can randomly simulate the characteristic of the assembly by simply using the distribution which represents the assembly process or the probability of conforming characteristic of the assembly process in the normal process condition. The second part is when the characteristic of one component or more is non-conforming. The simulator cannot simulate the characteristic by using either the process's distribution or the probability of conforming characteristic of the assembly process alone. The model which simulates the characteristic must be influenced by the component's quality and the model differs depending on the characteristic type of the component.

For the variable characteristic case, the assumption is that the machined part, which has the characteristic that falls outside the specification limit but still inside the minimum and maximum acceptable limits, can still be possibly assembled. The minimum and maximum acceptable limits can be determined from the tolerances of other components which will be assembled together with the simulated part.

If the characteristic of the machined part falls between specification limits and acceptable limits, then the probability of non-conforming in assembly process increases as compared to the probability in the normal process condition. The probability keeps on increasing until it reaches the minimum or maximum acceptable limit. Therefore, distance ratio is introduced in order to calculate how the probability of non-conforming characteristic in assembly process changes. The distance ratio is illustrated in Figure 3.2.

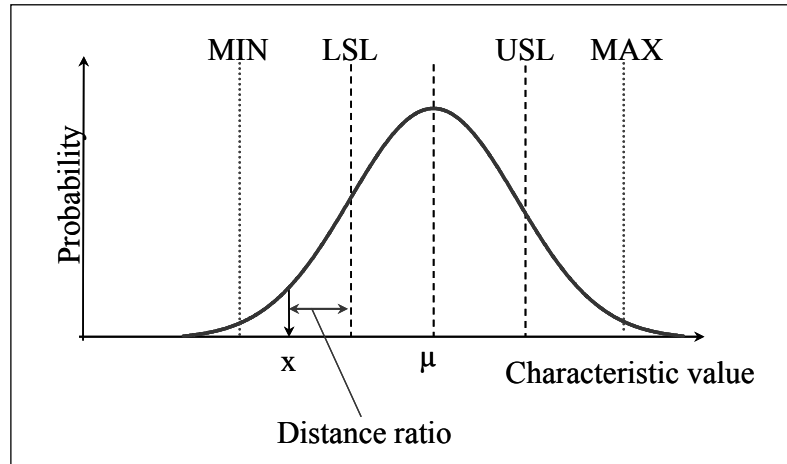


Figure 3.2: Example of distance ratio

The ratio of distance of machined characteristic can be calculated by the following equations:

if X is lower than lower specification limit,

$$\text{Distance ratio}_j = (LSL_j - X_j) / (LSL_j - MIN_j) \quad (3.1)$$

if X is higher than upper specification limit,

$$\text{Distance ratio}_j = (X_j - USL_j) / (MAX_j - USL_j) \quad (3.2)$$

where j is characteristic j ; for $j = 1, \dots, m$

The distance ratio gives no effect on the assembly's quality when the component's characteristic falls inside the specification limit. This means that the distance ratio is set to zero. The assembly part turns out to be a bad part when the distance ratio falls out of the acceptable limit or the distance ratio is set to be equal to one.

Each machined characteristic has different impact on the quality of assembly part. Another variable called importance factor is initiated at this point to integrate these impacts into the model. The importance factor, which can be determined from the historical data, ranges from zero to one. It should be multiplied with the distance ratio. The multiplication of distance ratio and importance factor of characteristic is called the characteristic's influence factor.

The influence factor of the component is the combination of influence factors of related characteristics. Furthermore, the influence factor of the whole assembly can be found from its related components' influence factor. It is assumed that the effects of component characteristics on the assembly are independent to each other, thus the influence factor for component and assembly can be derived from the following formulas:

$$\text{Influence factor}_i = 1 - \prod_{j=1}^m [1 - (\text{distance ratio}_j * \text{importance factor}_j)] \quad (3.3)$$

$$\text{Influence factor for assembly} = 1 - \prod_{i=1}^n [1 - \text{influence factor}_i] \quad (3.4)$$

where i is component i ; for $i = 1, \dots, n$
 j is characteristic j of component i ; for $j = 1, \dots, m$

As mention at the beginning of this section, the quality characteristic of assembly process is represented by a certain distribution depending on type of characteristic. The influence factor for assembly will affect the model either on assembly process's distribution or on the conforming probability of assembly characteristics. Besides, the distribution is influenced by failure and maintenance as in manufacturing process. Therefore the model is adjusted according to time depending on influence factor for assembly, failure, and maintenance. The assembly can obtain the characteristic value from this new adjusted model.

Figure 3.3 shows the example of how SixSigma generates the actual distribution of quality characteristic for assembly process. Normal distribution is used as an example. The process gets worse when there is a failure or the assembly's influence factor is more than zero. In this case, the mean of the distribution will shift or the standard deviation will increase. If the maintenance is performed and the assembly's influence factor is equal to zero, the distribution can be set back to its original position and the process capability can be at maximum since there is no disruption in the process.

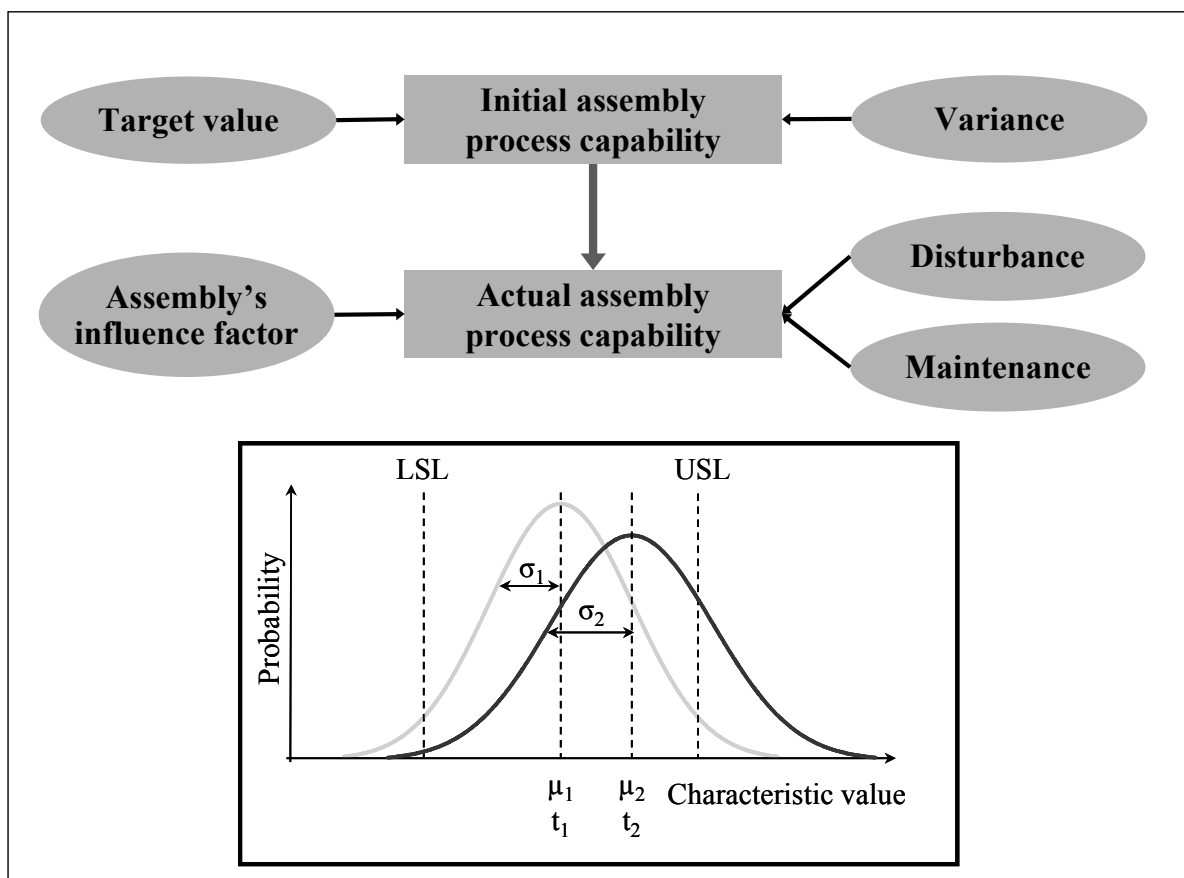


Figure 3.3: Example of how SixSigma generates the actual distribution of quality characteristic for assembly process

3.1.4 Inspection process

The inspection process is simulated in a similar way as the inspection process in QUINTE simulator. Due to bias and precision, the value given by the inspection tool may differ from the true value. The capability of the inspection process is described by a statistical distribution either by normal or Bernoulli distribution. Normal distribution is used to describe the inspection process of variable characteristics while Bernoulli distribution is used to describe the inspection process of attribute characteristics.

In QUINTE simulator, capability of inspection process is assumed to be constant over time which does not mimic the reality. In reality, inspection process capability is not constant over time. In case of variable characteristics, the expected value can glide from its original value or the deviation can increase because of wear of the tool, etc. in the same way as in the manufacturing process. Therefore, in this SixSigma simulator, the mean μ_{insp} shifts from the given machined characteristic value from manufacturing process according to time. The standard deviation σ_{insp} must as well change over time. The distribution can be restored or improved by setting up and calibration.

This concept is also applied for the inspection process of attribute characteristics. The accuracy of the inspection process decreases according to time and it can be restored or improved by setting up and calibration.

The simulator generates random inspected value from the actual distribution. The inspected value will be compared with the specification limit, thus deciding whether or not the part conforms. The occurrences of decision errors (type I and type II error) are also collected as the output performance by the simulator.

After the decision is made, the part, which is declared as a conformed part, continues on its production sequence. Scraps must be sorted out. The rework parts can be handled in two ways. The first option is that the rework parts can be set back to the preceding process or processes and the operation can be repeated. Another option is to repair the part in a separated rework area.

3.2 SIXSIGMA IN ARENA®

The simulator QUINTE was originally built on C/C++ language and it was successfully tested in the industries. However, there are some minor drawbacks in QUINTE; for example, there is no animation for the simulation, only limited process distributions can be modelled, and it is difficult to modify or enhance other components or functions in QUINTE without strong knowledge in C/C++. In order to overcome these shortcomings, the new SixSigma simulator was developed in a commercial simulation software called Arena®. With this SixSigma environment, the user has an opportunity to create and animate the processes, use Arena's statistical analyzer, and use other Arena's user-friendly functions. Moreover, SixSigma can easily be modified or enhanced by the developer without a need for programming since Arena is very easy to use with its point and click interface and fill in the blank dialogue boxes.

SixSigma functions are now placed in Arena's template as shown in Figure 3.4. The SixSigma template consists of 10 modules. This SixSigma template can be used together with

other Arena's template in order to build a simulation model. The followings are the description of each module in SixSigma template. This section also gives the review of some other important modules in Arena's template.

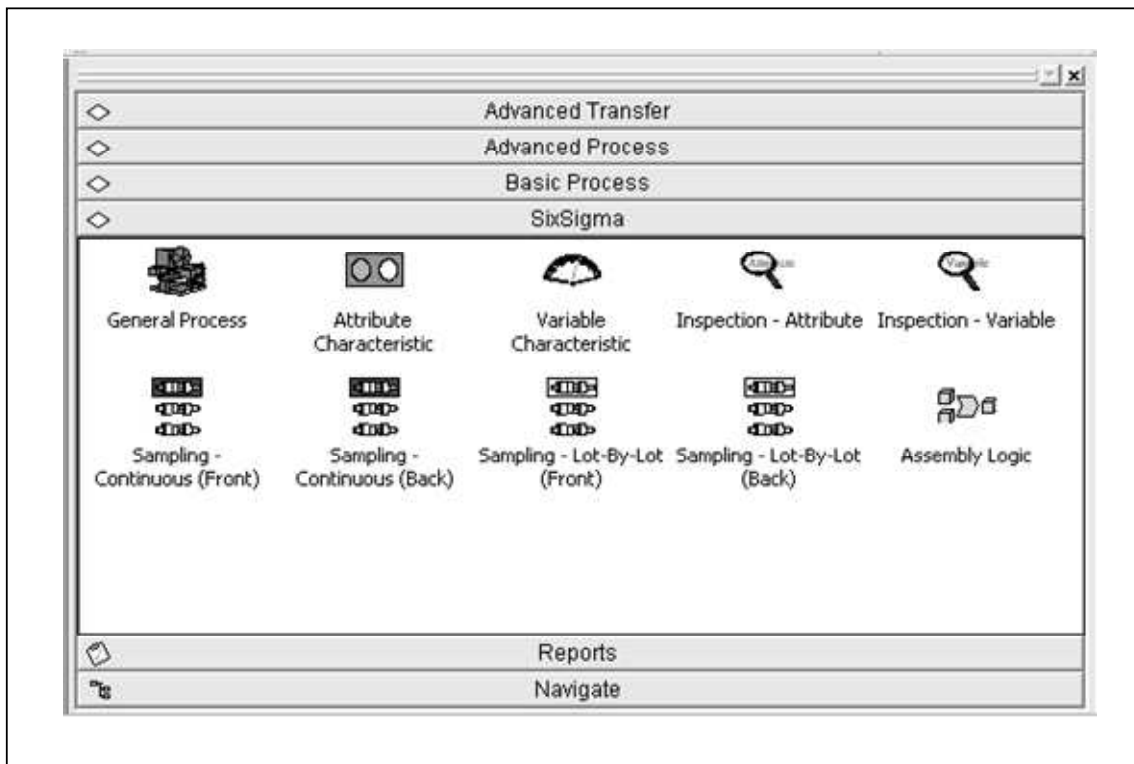


Figure 3.4: SixSigma template in Arena®

3.2.1 Process module

The first module is the “General Process” module. This module is designed for any processes in the production such as manufacturing, inspection, or assembly process. The user can assign the process name, processing time, cost allocation, processing cost and information about failure and maintenance. The processing time can be given in a form of distribution or constant value. 13 fundamental statistical distributions are available to choose from. These distributions are exponential, normal, triangular, uniform, erlang, beta, gamma, Johnson, lognormal, poisson, weibull, continuous (empirical) and discrete (empirical) distribution, The cost of processing the parts can be allocated as value added, non-value added, transfer, wait, or other cost. Processing cost should be given in the unit of Euro per hour. The interval between failures and between maintenances can be assigned based on the number of produced entities or time. The user view and dialog of “General Process” module is shown in Figure 3.5.

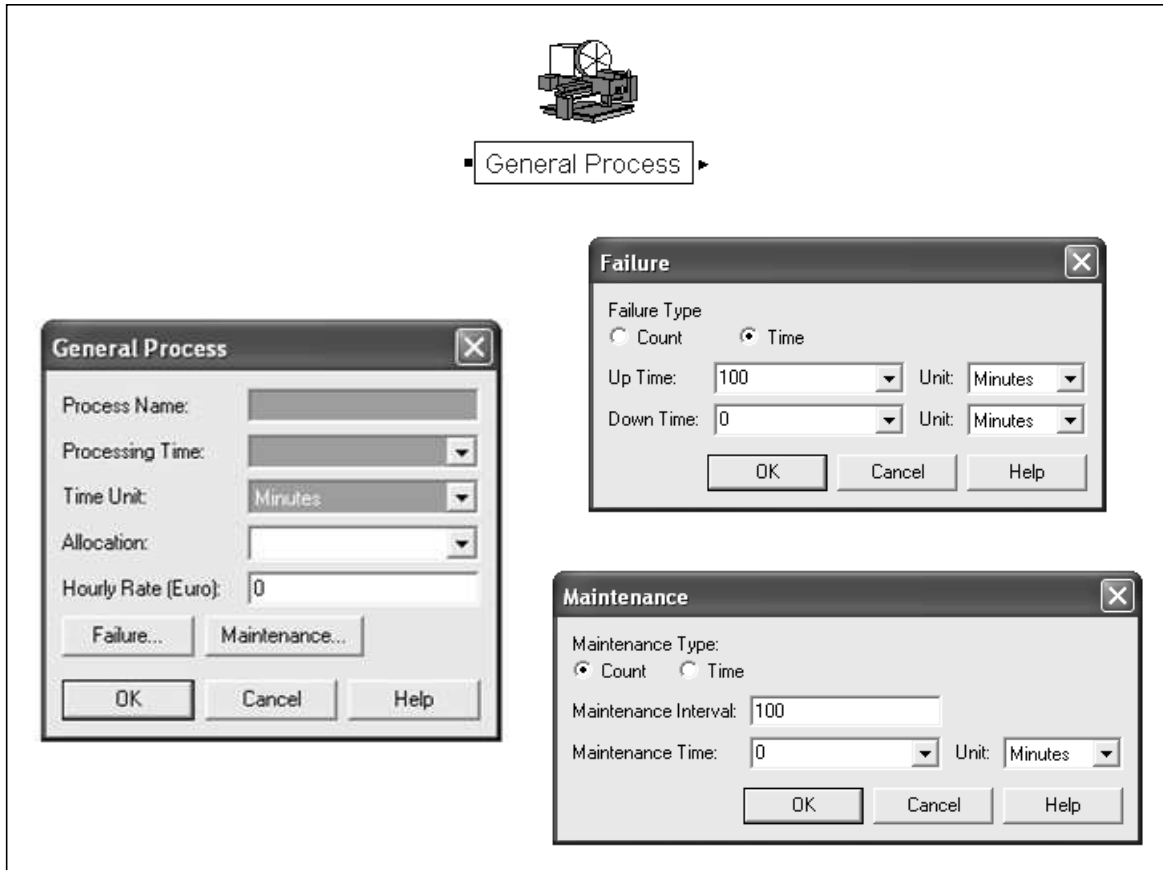


Figure 3.5: General Process module user view and dialog

The logic of “General Process” module is represented in a form of flowchart in Figure 3.6.

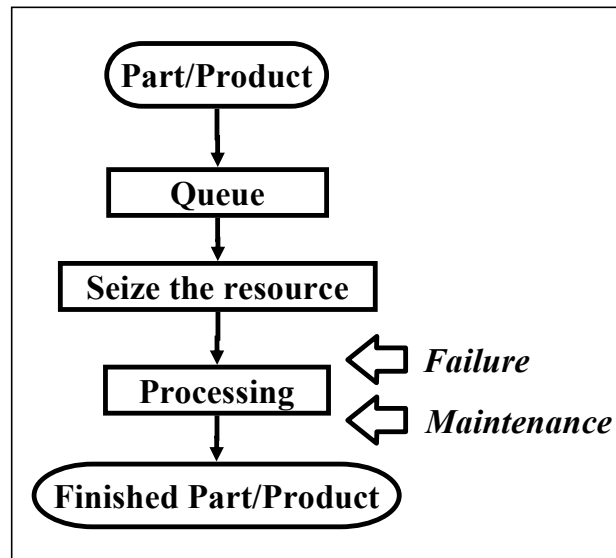


Figure 3.6: General Process module logic

The figure shows that the process is affected by failure and maintenance. When failure occurs, the part, which is still being operated by the machine, will be stopped and its

operating can be continued after the repair. On the other hand, maintenance will perform only when the current job is finished. After the maintenance, the machine will be in operating state and the next maintenance is scheduled. The ways failure and maintenance influence the process are shown in Figure 3.7.

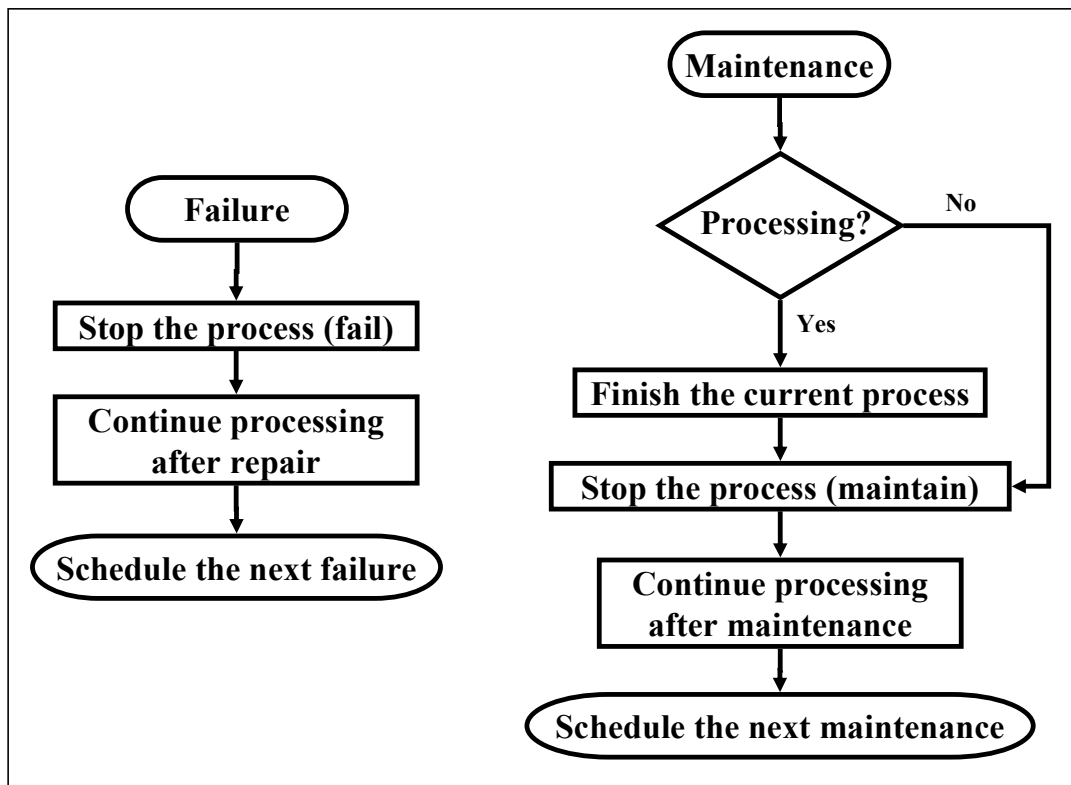


Figure 3.7: Failure and Maintenance logic in General Process module

3.2.2 Characteristic assignment modules

There are two modules for the quality characteristic assignment: “Attribute Characteristic” and “Variable Characteristic” modules. The information about the type of the produced part, type of process, characteristic, its distribution, and the specification can be defined here. The importance factor is needed if the produced part type is component or subassembly.

3.2.2.1 Attribute Characteristic module

The distribution for attribute characteristic is Bernoulli distribution. The probability of conforming characteristic, which is denoted by p , can be put into the simulation in a form of conformity rate. Conformity rate (%) is equal to $p*100$.

As described earlier, SixSigma can model the distribution dynamically. The deviation of distribution or conformity rate can be assigned under the “Conformity Rate Change...” dialog box. The user can specify how often the conformity rate should change and also the change or reduction of conformity rate in percentage. The name of process which produces this characteristic must be entered as well in order to initialize the change factor when the machine

is set up or maintained. When the dynamic distribution is not required to be modelled, the fields for rate change can be left blank. The user view and dialog of “Attribute Characteristic” module is shown in Figure 3.8.

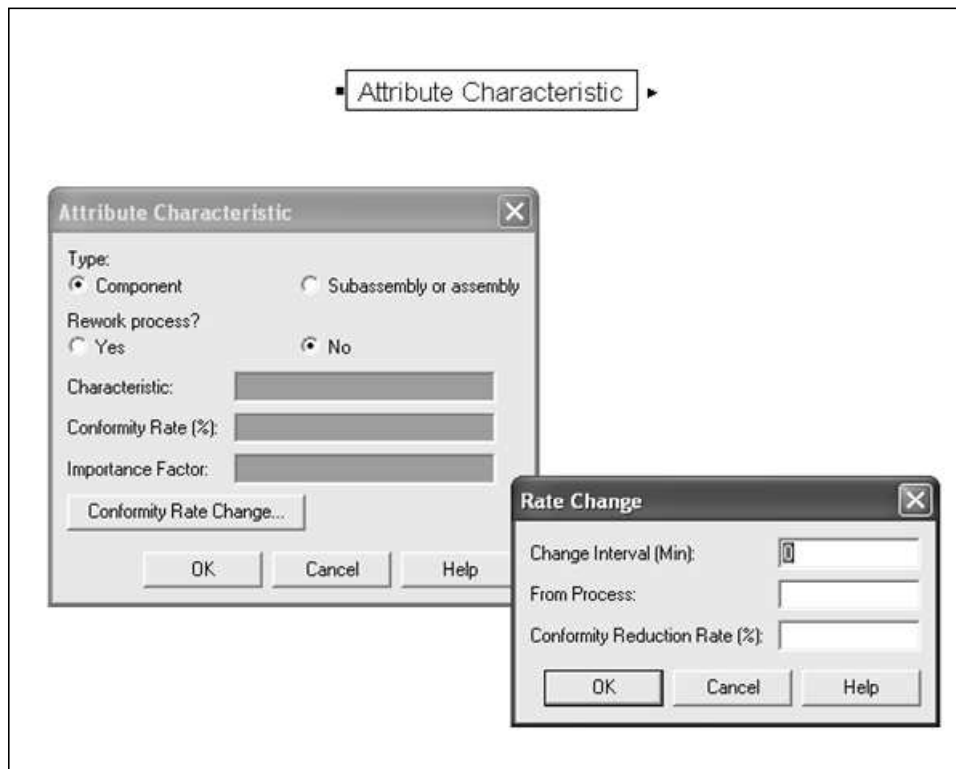


Figure 3.8: Attribute Characteristic module user view and dialog

The simulator creates the so called “change factor” from the change interval, state of the machine, and the conformity reduction rate. The change factor is updated every change interval. Before it is updated, the machine that produces the related characteristic is checked if it is maintained. If the machine is maintained, the change factor is reset to zero. If the machine is not maintained, the change factor will increase according to the conformity reduction rate. The logic of change factor formation in the SixSigma is shown in Figure 3.9. This logic is also applied in all module, which has the change in distribution, i.e. “Variable Characteristic” module and inspection modules. However, the change factor update will not be activated if the fields in rate change dialog or distribution change dialog are left blank.

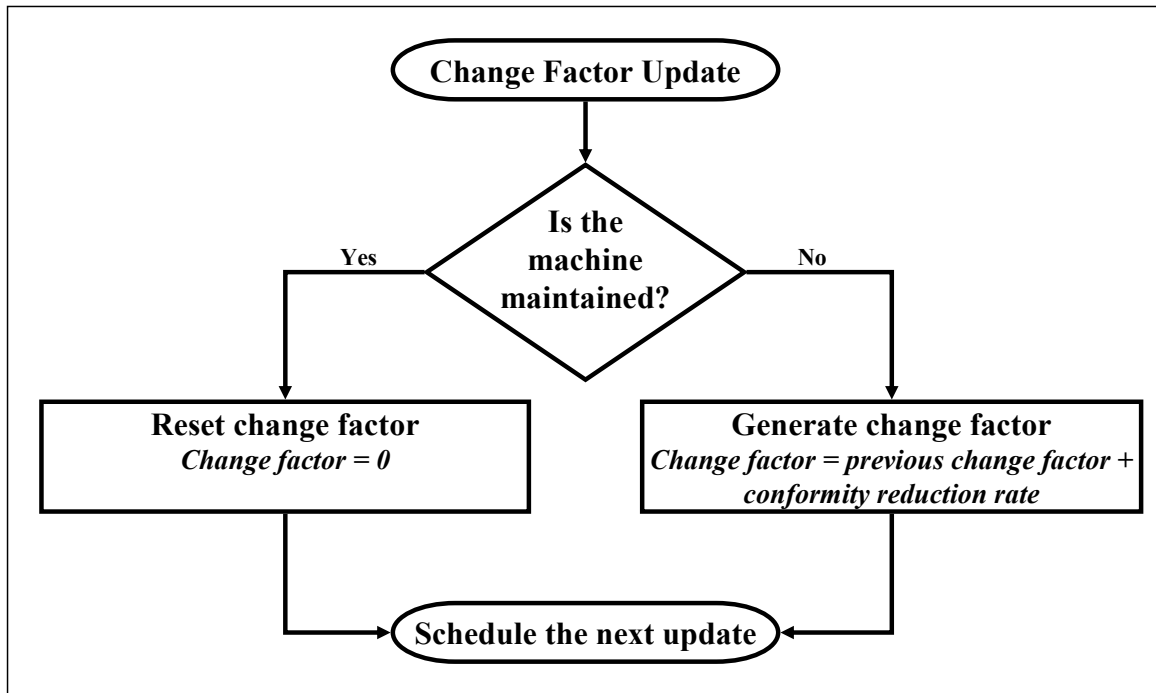


Figure 3.9: Change Factor update logic

The logic behind the Attribute Characteristic module is shown in Figure 3.10 to 3.12. First the part will be checked if it is a reworked part. If the part just has been reworked in the previous process, it will get the new characteristic value and the previous distance ratio for the reworked characteristic will be deleted from the part. The previous distance ratio will be stored as a value called “old distance ratio” before it gets the new characteristic value and distance ratio.

The part will also be checked if it is a component. If the part is a component, the actual conformity rate will be generated according to the input conformity rate and the change factor. If the part is subassembly or assembly, the actual conformity rate will be generated according to the input conformity rate, change factor and the influence factor for assembly. After the actual conformity rate is defined, the simulator simulates the characteristic based on this conformity rate.

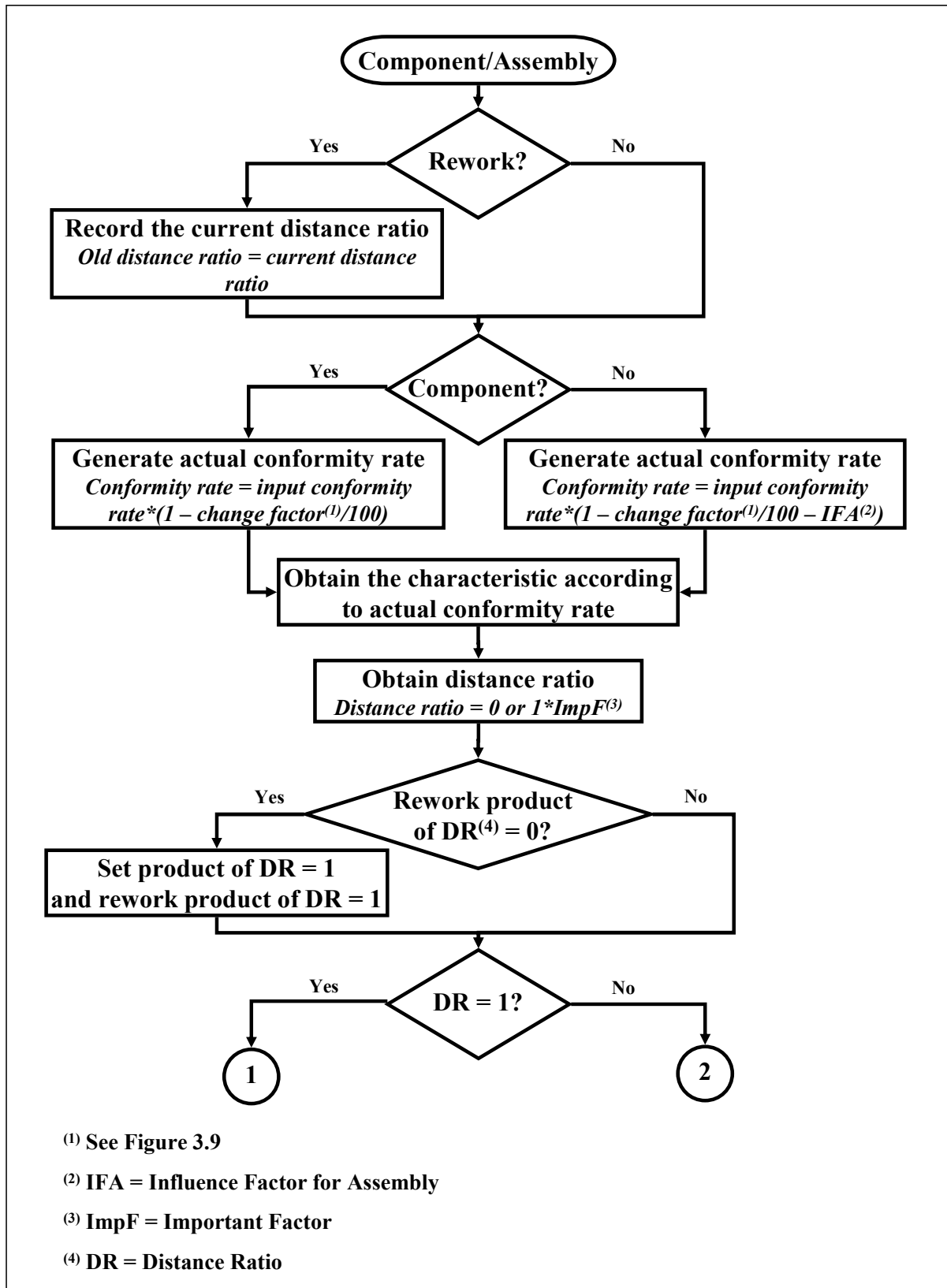


Figure 3.10: Attribute Characteristic module logic (1)

From the characteristic value, the simulator calculates the distance ratio for this characteristic. And the product of all distance ratios will be calculated and assigned later on before leaving the module based on the distance ratio. The followings are the formulas for the calculation.

When the produced characteristic value = 1 or the part is good:

$$\text{Distance ratio of the characteristic} = 0 \quad (3.5)$$

When the produced characteristic value = 0 or the part is bad:

$$\text{Distance ratio of the characteristic} = 1 * \text{Important Factor} \quad (3.6)$$

The product of distance ratios of all characteristics that have been produced so far:

$$\text{Product of DR} = \text{Previous product of DR} * (1 - \text{DR of the characteristic}) \quad (3.7)$$

where DR is Distance Ratio

Before the product of distance ratio is calculated, the simulation introduces an attribute called “rework product of DR” or “rework product of distance ratio”. It is the attribute which is the product of all created distance ratios except the distance ratio that is equal to 0. The rework product of distance ratio is calculated in the same way as product of distance ratio but it excludes the non-conformity or the characteristic that has distance ratio value of one.

In Figure 3.10, it is shown that after the product gets the distance ratio, the simulator checks the value of rework product of distance ratio if it is equal to 0 or not. If it is zero, then it means that this current characteristic is the first characteristic that going to be assigned or produced. Therefore, the initial value of the product of distance ratio and rework product of distance ratio has to be set up as one.

After that the distance ratio will be checked if it is one or not. If the distance ratio is equal to one, then the product of distance ratio will be zero. This will make all the other distance ratios from the previous created characteristics impossible to be traced back, when the bad characteristic has been reworked. The rework product of DR is used here in order to keep the product of distance ratio of other characteristics that are not the bad ones.

If the distance ratio is one, it will be checked once again if the part is a reworked part (see Figure 3.11). If it is a reworked part, the old distance ratio has to be taken out from the rework product of distance ratio before the part gets the new product of distance ratio. However, the old distance ratio is not necessary to be taken off when the old distance ratio is equal to zero or one.

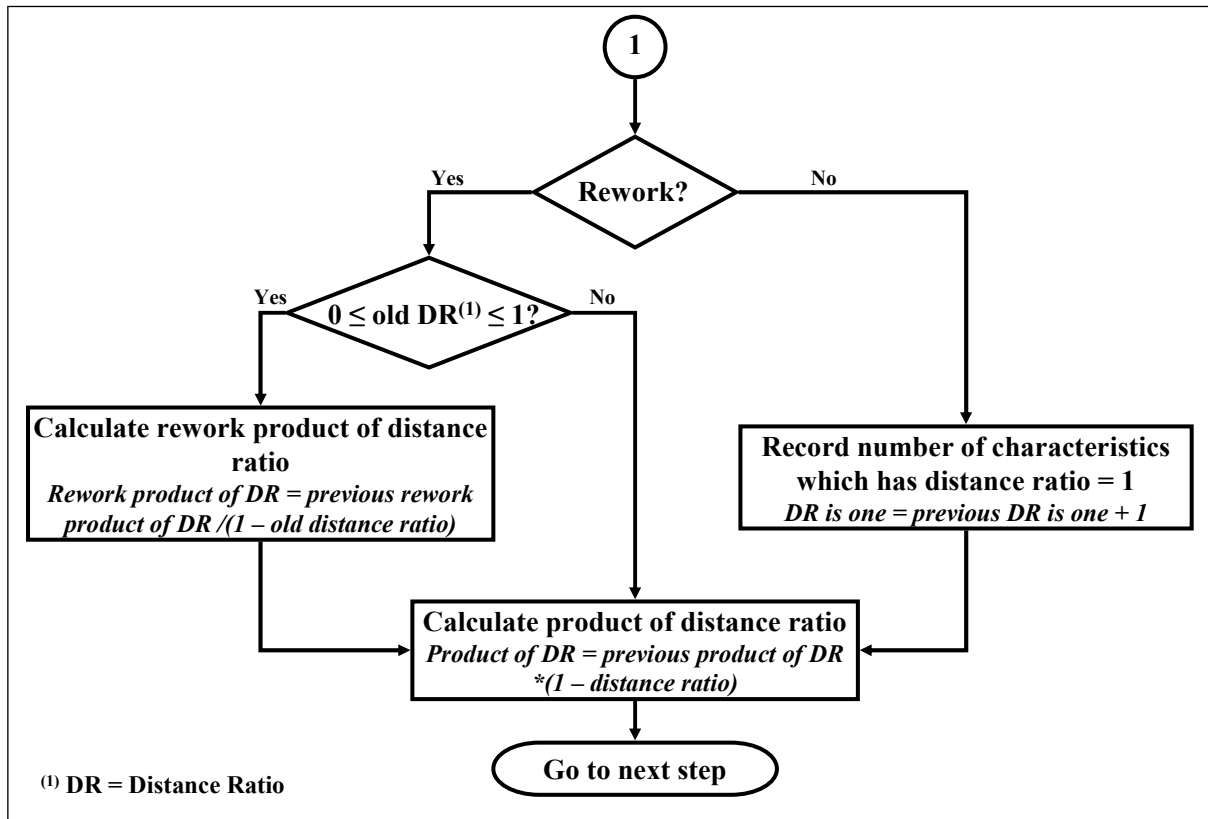


Figure 3.11: Attribute Characteristic module logic (2)

If the part is not a reworked part, the simulator will record the number of distance ratios which are equal to one for this part. The simulator can tell how many bad characteristic in this specific part from the attribute “DR is one”. Then the part will be assigned with the new product of distance ratio.

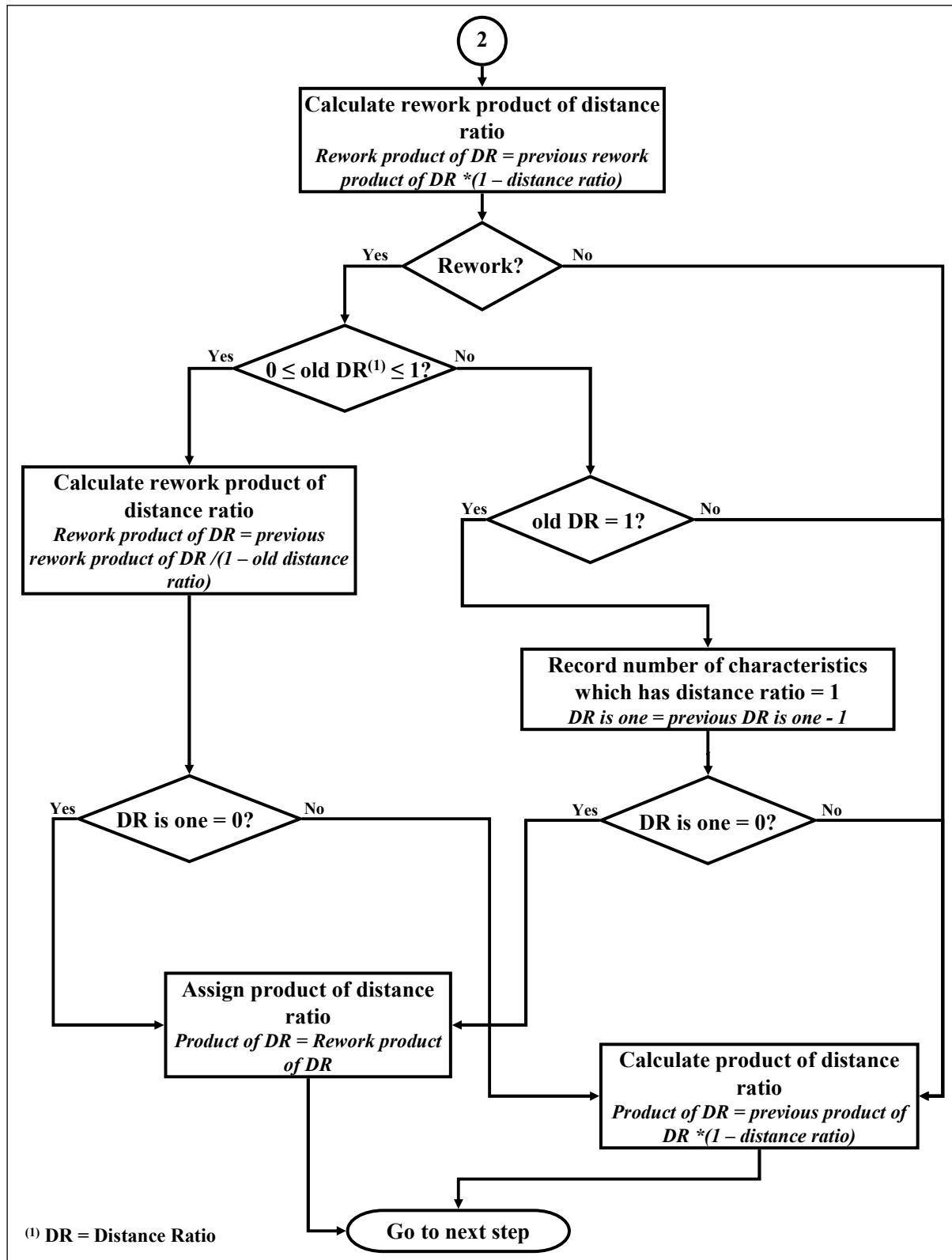


Figure 3.12: Attribute Characteristic module logic (3)

Figure 3.12 shows the logic of how the simulator assigns the product of distance ratio and also the rework product of distance ratio when the distance ratio is not equal to one. The rework product of DR is calculated first before deleting the old distance ratio from the value.

The part will be checked if it is a reworked part or not. If the part is not a reworked part, the part does not hold any distance ratio for the characteristic before. Therefore, the part will receive the product of distance ratio and go to the next step.

If the part is a reworked part, the old distance has to be removed from the rework product of distance ratio. After that the part will be checked for the number of bad characteristic. If there is no more characteristic that has distance ratio equal to zero, then the product of distance ratio, which is given to the part, is equal to the rework product of distance ratio. Otherwise, the product of distance ratio is calculated in the typical way.

There are special cases for the parts which have old distance ratio equal to zero and one. If the part is a reworked part but has the old distance ratio equal to zero, the part will receive the product of distance ratio and proceed to the next step. Since the old distance ratio does not manipulate the product of distance ratio.

If the reworked part has the old distance ratio equal to one, then the number of bad characteristic or the attribute “DR is one” has to be deducted by one because this characteristic has passed the reworked process and it does not contain the distance ratio of one anymore. The simulator will afterwards check if this is the last characteristic that has distance ratio equal to one or not. If it is the last bad characteristic, the product of distance ratio is set to be equal to rework product of distance ratio. Otherwise, the product of distance ratio is calculated with the standard formula for product of distance ratio. After the part gets the product of distance ratio value, it will proceed to the next step.

3.2.2.2 Variable Characteristic module

Variable characteristic can be simulated from 10 distributions. The offered distributions are exponential, normal, triangular, uniform, erlang, beta, gamma, lognormal, poisson, and weibull distribution. The upper and lower specification limits as well as the minimum and maximum acceptable limits must be entered here. The user view and dialog of “Variable Characteristic” module is shown in Figure 3.13.

The deviation of distribution can be assigned under the “Distribution Change...” dialog box. Similar to “Attribute Characteristic” module, the user can specify how often the distribution should change and also the change parameter. The number of required change parameters depends on the distribution. For example, normal distribution needs two change parameters; the first one is for the mean and the second one is for the standard deviation. The change parameter(s) is updated in the same way as the change factor in attribute characteristic module.

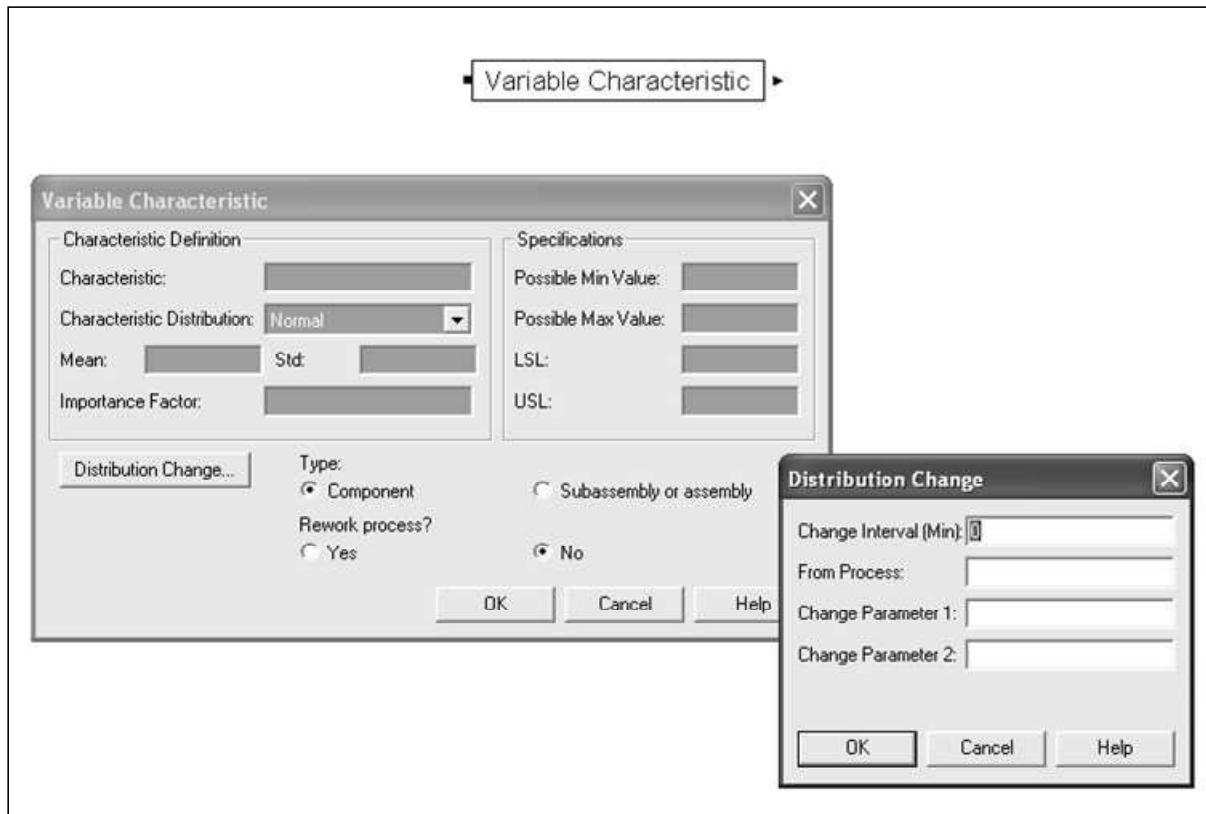


Figure 3.13: Variable Characteristic module user view and dialog

The logic of the Variable Characteristic module is shown in Figure 3.14 to 3.16. They are similar to the logic of the Attribute Characteristic module. The difference is where the simulator assigns the characteristic value and the distance ratio.

The characteristic value is not generated according to the conformity rate but according to the distribution (see Figure 3.14). If the part is a component, the actual distribution of the characteristic will be generated according to the input distribution parameter(s) and the change factor. If the part is subassembly or assembly, the actual distribution of the characteristic will be generated according to the input distribution parameter(s), change factor and the influence factor for assembly. After the actual distribution is defined, the simulator simulates the characteristic based on this distribution.

From the characteristic value, the simulator calculates the distance ratio for this characteristic. And the product of all distance ratios will be calculated and assigned later on before leaving the module based on the distance ratio. There are four possible solutions for the distance ratio.

- Case 1: If characteristic falls within specification limits, then distance ratio = 0.
- Case 2: If characteristic falls outside acceptable limits, then distance ratio = 1.
- Case 3: If characteristic falls between lower specification limit and lower acceptable limit, then distance ratio is calculated from equation 3.1.
- Case 4: If characteristic falls between upper specification limit and upper acceptable limit, then distance ratio is calculated from equation 3.2.

The product of distance ratios of all characteristics that have been produced so far is calculated, similar to the attribute characteristic module, from equation 3.7.

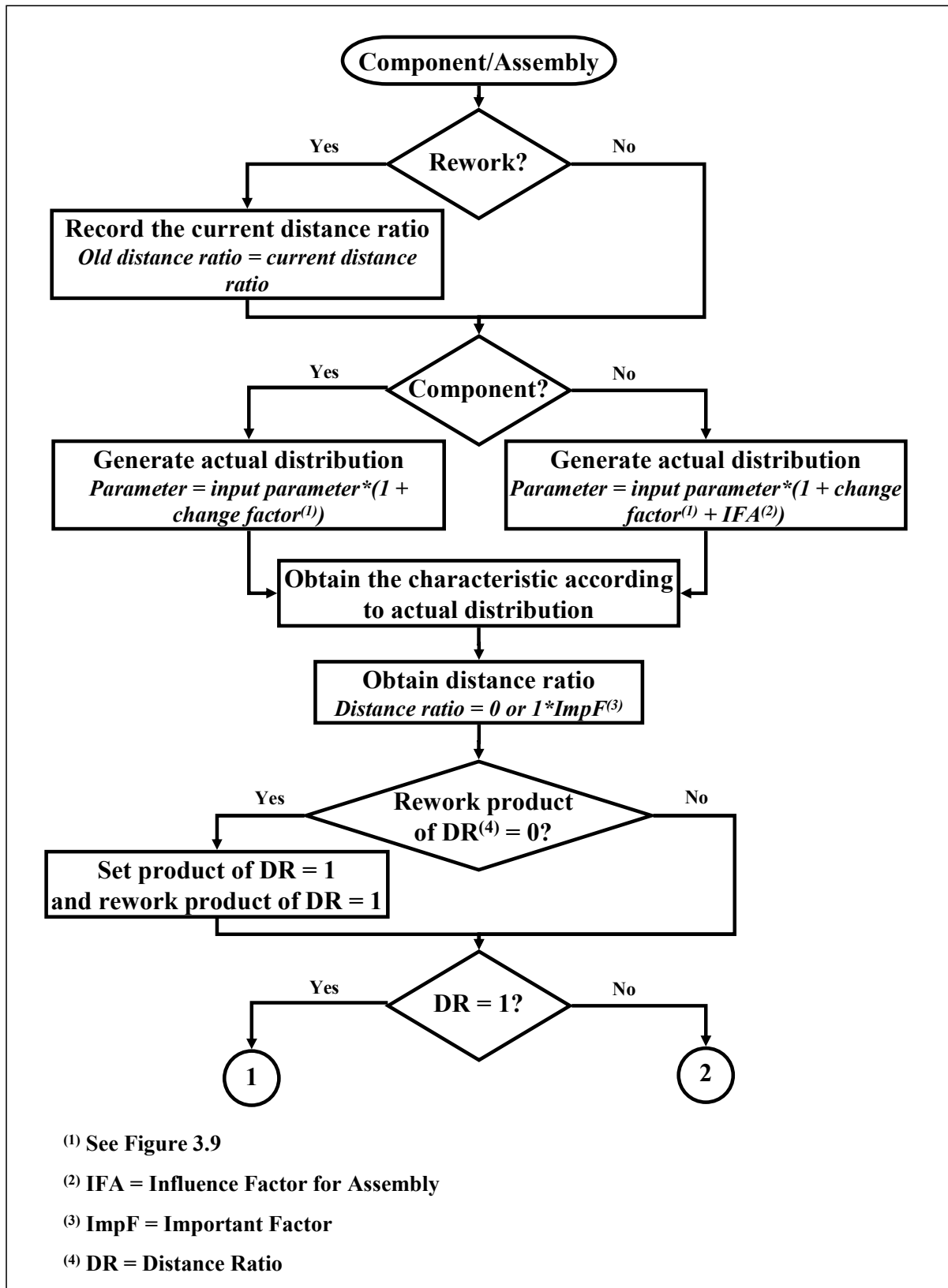


Figure 3.14: Variable Characteristic module logic (1)

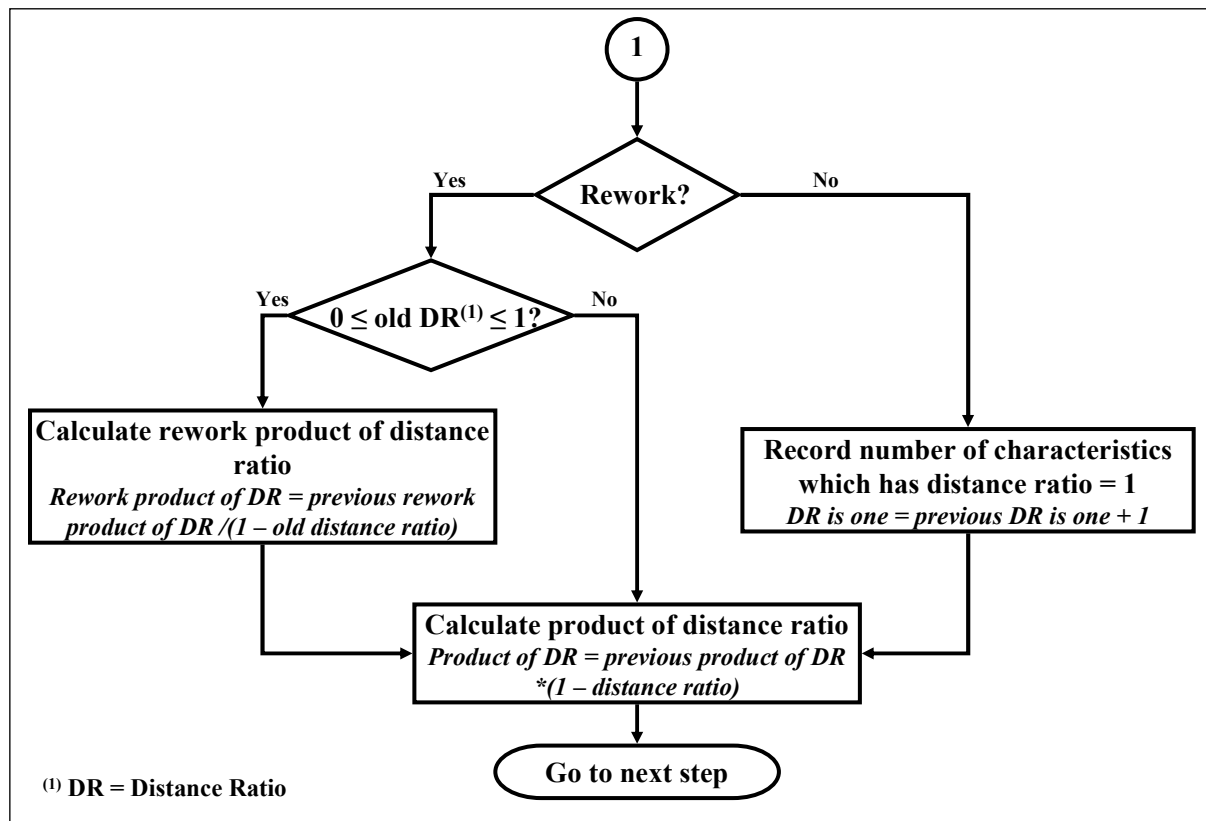


Figure 3.15: Variable Characteristic module logic (2)

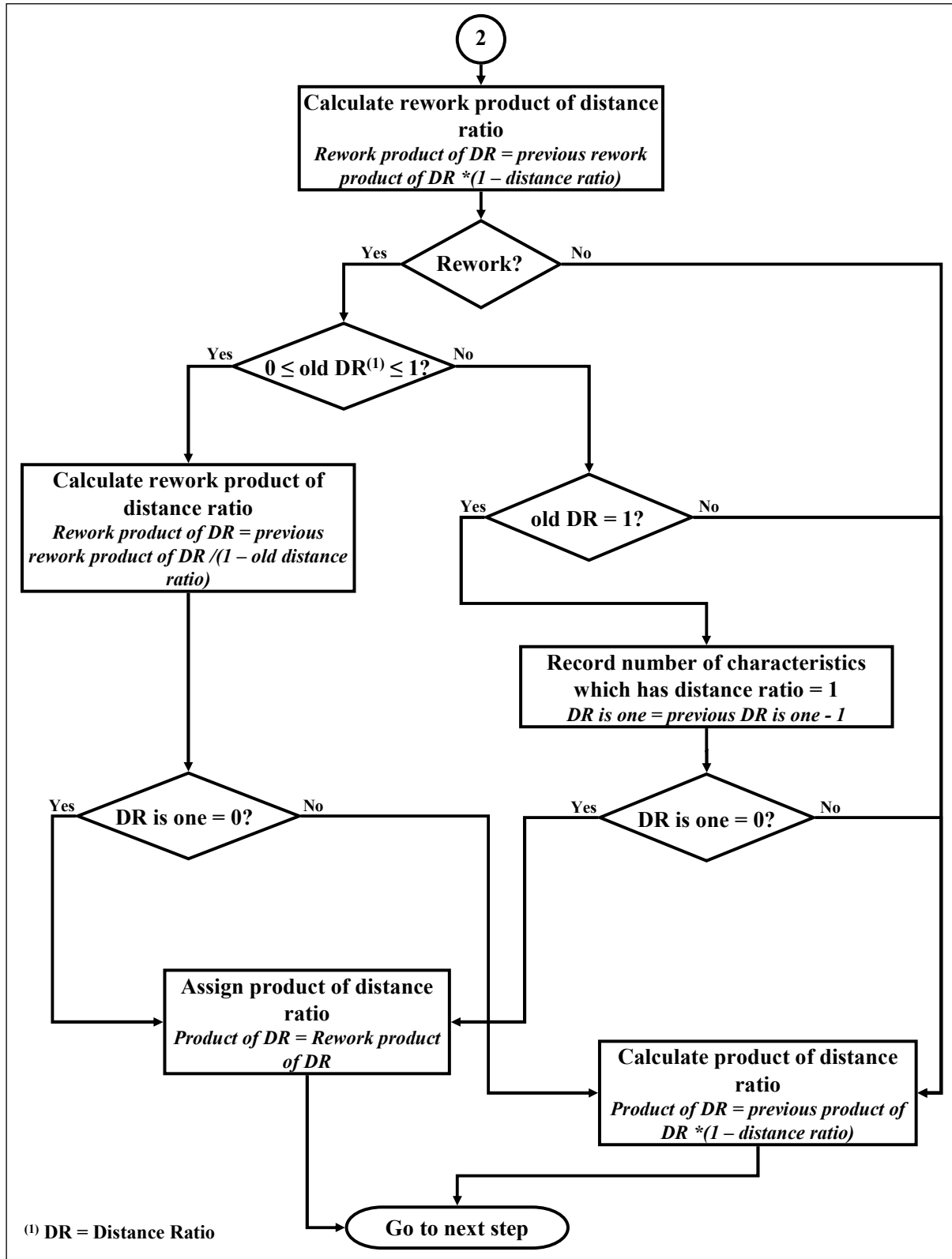


Figure 3.16: Variable Characteristic module logic (3)

3.2.3 Inspection modules

The information about inspection equipment can be added in the “Inspection – Attribute” or “Inspection – Variable” modules according to the type of quality characteristic that the equipment can measure.

3.2.3.1 Inspection – Attribute module

In the “Inspection – Attribute” module (Figure 3.17), the inspected characteristic and the accuracy of inspection equipment must be defined. The policy for nonconformity, if it will be reworked or scraped, has to be chosen. The user can specify the name of rework station or the field can be left as “None”. If the rework station is “None”, the user has to manually connect the rework exit point to the next production step in Arena’s model window. There are two exit points from the user view in Figure 3.17. The upper exit point is the exit point of the conformities and the lower exit point is the exit point of nonconformities, both scrap and rework parts.

In both inspection modules, the user has the possibility to add the change in inspection accuracy over time in the same way as in “Attribute Characteristic” and “Variable Characteristic” modules.

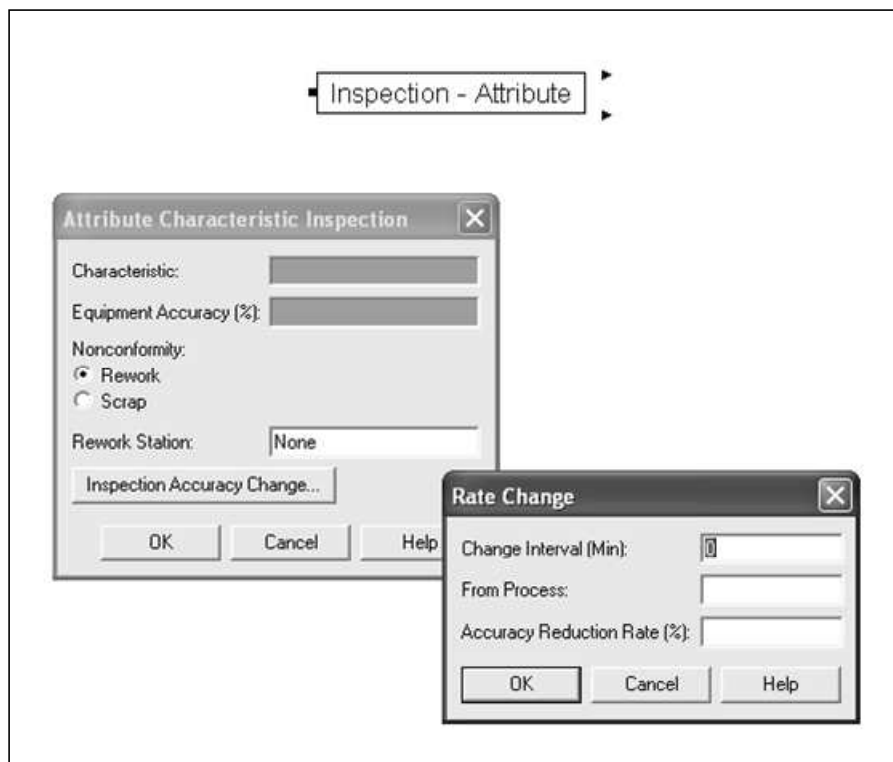


Figure 3.17: Inspection – Attribute module user view and dialog

The actual inspection accuracy is built according to the input inspection accuracy and the change factor. The simulator simulates the inspected value of the characteristic from this inspection accuracy. After that the part will be checked for the characteristic if the

characteristic value that the part get from manufacturing process or assembly process is good (value = 1) or bad (value = 0). The characteristic value will be compared with the inspected value. If the inspected value is the same as the characteristic value, then the inspection is done correctly. If the inspected value is not the same as the characteristic value, then there is an inspection error. Type I and type II errors are recorded in the database. The part will be sent to the next step if it is declared as a good part (inspected value = 1) or it will be sent to rework or scrap depending on the nonconformity policy if it is declared as a bad part (inspected value = 0). The logic that described above is summarised in Figure 3.18.

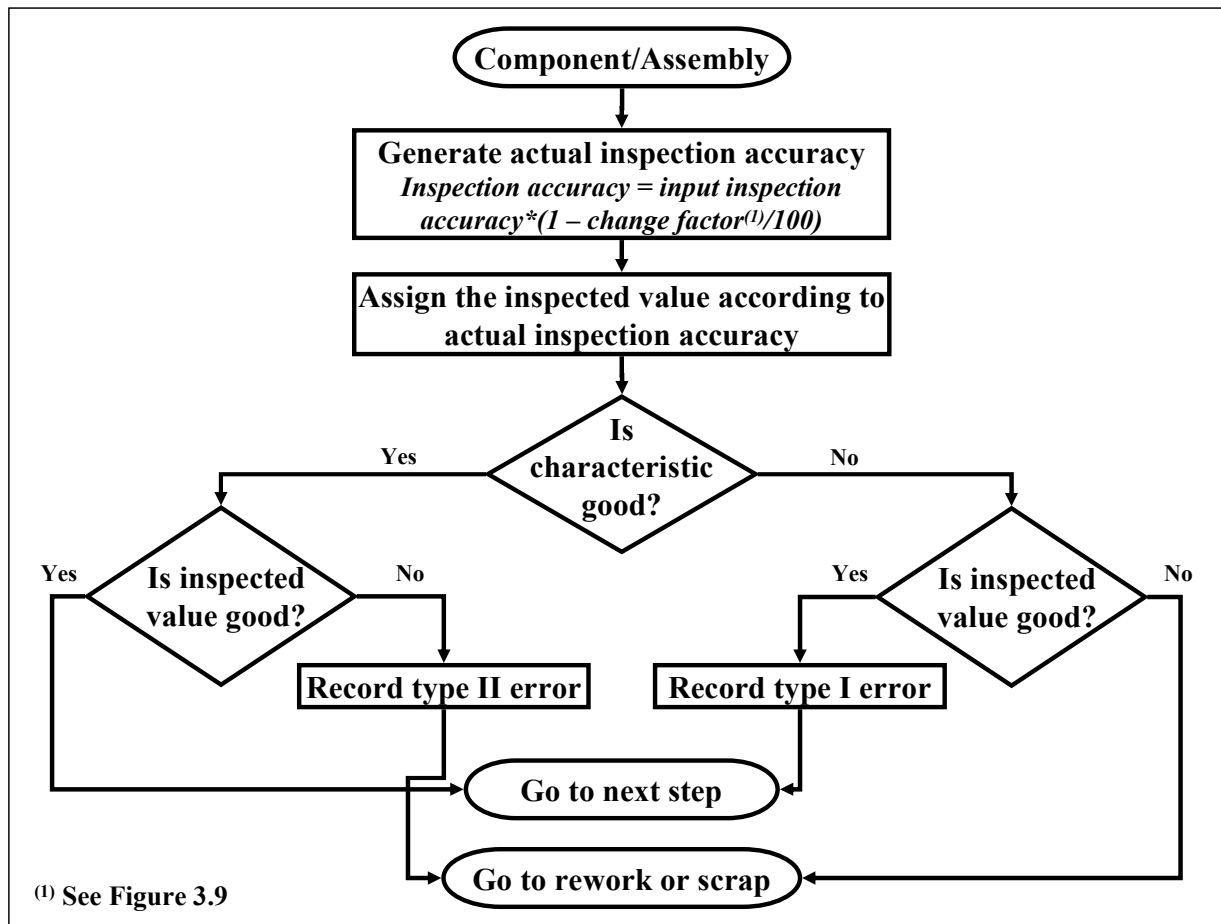


Figure 3.18: Inspection – Attribute module logic

3.2.3.2 Inspection – Variable module

In addition to the inspected characteristic, the accuracy of the inspection equipment must also be defined in the “Inspection – Variable” module. However, an inspection uncertainty (u) and a confidence level are required instead of the percentage of accuracy. The uncertainty /Taylor00/ is usually based on scientific judgement using all of the relevant information available, which may include:

- previous measurement data,
- experience with, or general knowledge of, the behaviour and property of relevant equipments,

- manufacturer's specifications,
- data provided in calibration and other reports, and
- uncertainties assigned to reference data taken from handbooks.

In order to explain the concept of uncertainty, the author would like to illustrate the example of uncertainty statement. This example is taken from the website authored by Taylor /Taylor00/:

The measured mass $m_s = 100.02147$ g with a combined standard uncertainty (i.e. estimated standard deviation) of $u_c = 0.35$ mg. Since it can be assumed that the possible estimated values of the standard are approximately normally distributed with approximate standard deviation u_c , the unknown value of the standard is believed to lie in the interval $m_s \pm u_c$ with a level of confidence of approximately 68%.

The procedure of converting an uncertainty which is quoted in handbook, manufacturer's specification, etc. to a standard uncertainty is to treat the quoted uncertainty as if a normal distribution had been used to calculate it and divide it by the appropriate factor for such a distribution. These factors are, for example, 1.960 and 2.576 for 95% and 99% levels of confidence. In the "Inspection – Variable" module, the user has choices to choose between 95% and 99% levels of confidence.

The user has to specify the specification and acceptable limits. This information is needed for assigning the non-conformities. Non-conformities are handled in two ways; the part will be scrap if the inspected value falls outside acceptable limits and another way is the part will be reworked if the inspected value falls outside specification limits but still within the acceptable limits. Similar to "Inspection – Attribute" module, the name of rework station can be left as "None". If the rework station is "None", the user has to manually connect the rework exit point to the next production step in Arena's model window.

There are three exit points from the user view in Figure 3.19. The upper most exit point is the exit point of the conformities. The two lower exit points are the exit points of nonconformities; the middle one is for rework part and the lowest one is for scrap parts.

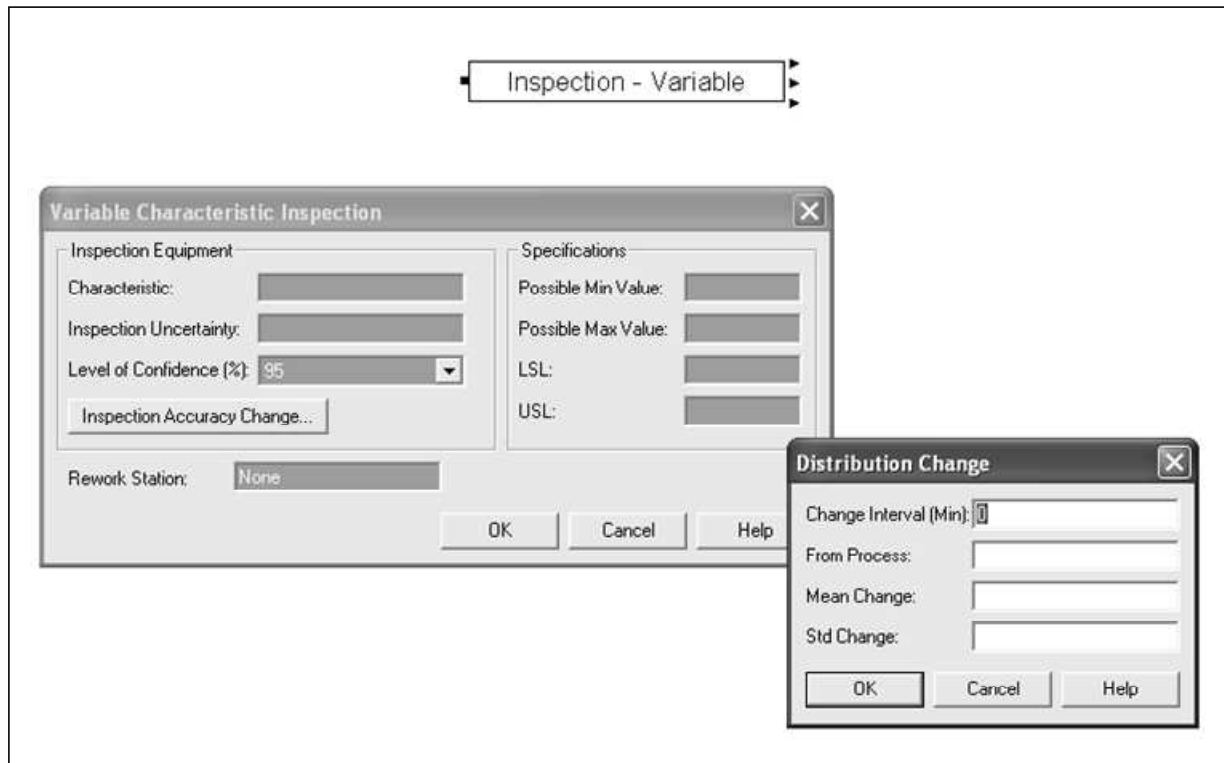


Figure 3.19: Inspection – Variable module user view and dialog

The logic of “Inspection – Variable” module is presented in Figure 3.20 and 3.21. The actual distribution for inspection process is generate when the part enter the module. The distribution for inspection process is represented by normal distribution. There are two parameters for this distribution; mean μ and standard deviation σ . Parameter of mean and standard deviation is generated according to the following equations. The change parameters in these equations are the same as described in section 3.2.2.2.

$$\mu = x*(1 + \text{change parameter for } \mu) \quad (3.8)$$

where x is characteristic x

$$\sigma = (u_c / \text{converting factor})*(1 + \text{change parameter for } \sigma) \quad (3.9)$$

where u_c is inspection uncertainty with c confidence interval

converting factor is 1.960 for 95% confidence interval and 2.576 for 99% confidence interval

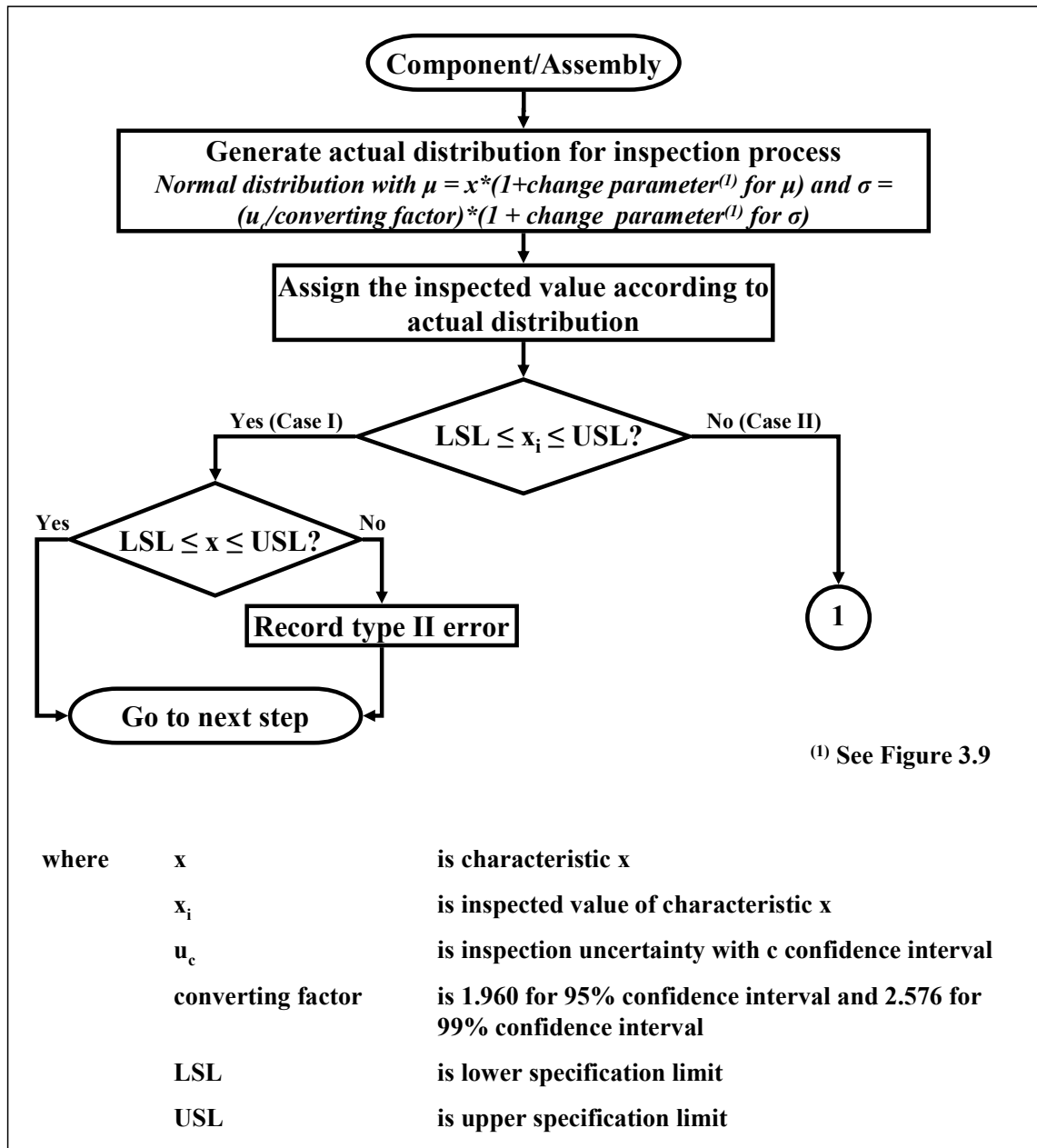


Figure 3.20: Inspection – Variable module logic (1)

The simulator simulates the inspected value according to the generated actual distribution. Then the module will check if the inspected value falls within the specification limits or not. If yes, the part will be in Case I situation. If no, the part will be in Case II situation.

Case I: The simulator will compare the inspected value with the characteristic value. When both of characteristic and inspected values fall within the specification limits, the part will continue to the next production sequence. If the inspected value does not match with the characteristic value, then the type II error will be recorded before the part is sent to the next step.

Case II: The part will be checked again if the inspected value falls within the acceptable limits or not. If the inspected value falls within the acceptable limits, the part will be in Case II-1. Otherwise, the part will be in Case II-2.

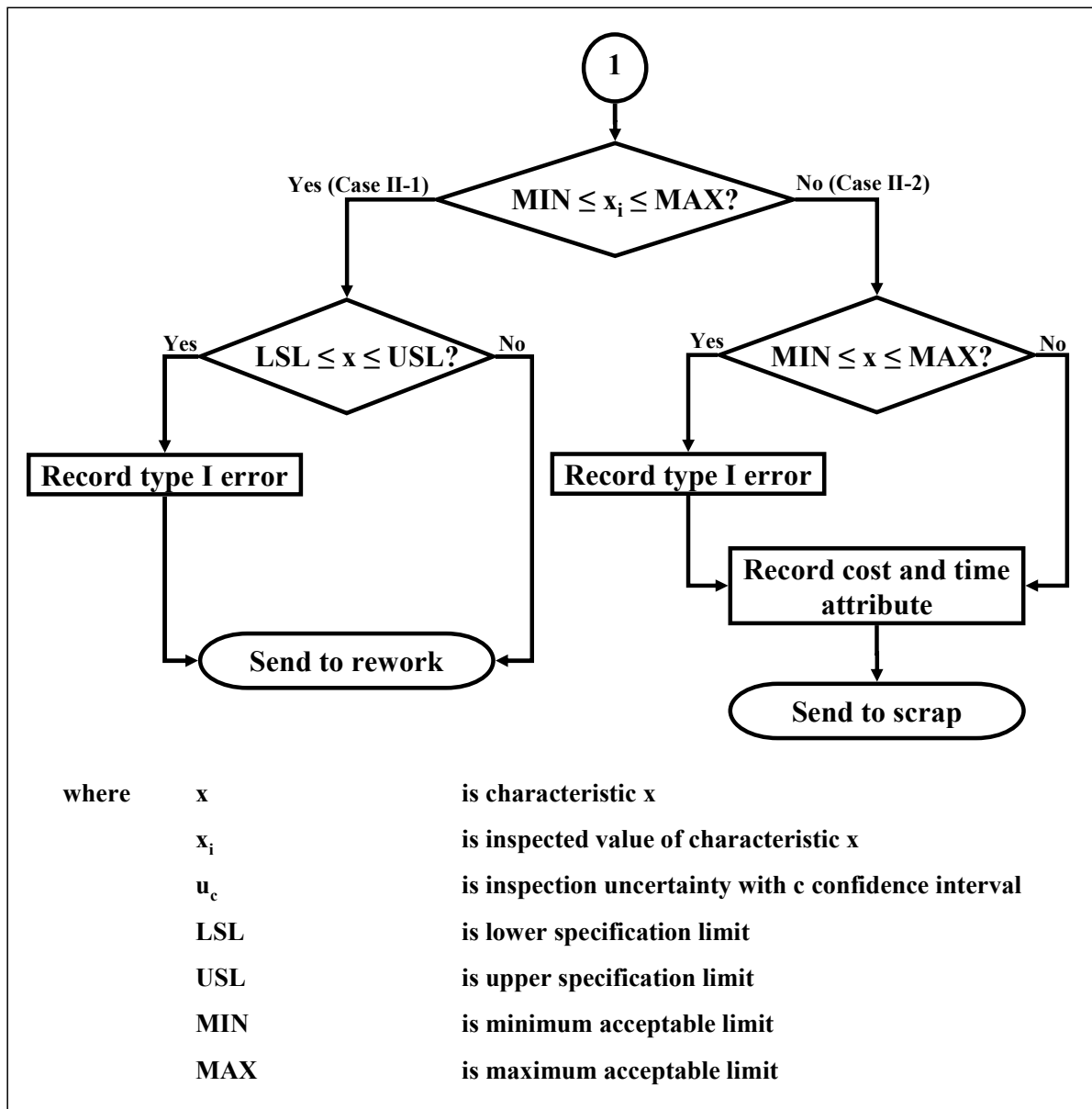


Figure 3.21: Inspection – Variable module logic (2)

Case II-1: The part will be checked if the characteristic value falls within specification limits or not. The aim of this procedure is to check if there is any error from the inspection process. If the characteristic falls within the specification limits, then it means that the inspected value is wrong. So the simulator will record this inspection error as a type I error. If the characteristic falls within specification limits, then the part will be sent to rework.

Case II-2: The simulator will compare the inspected value with the characteristic value. If the characteristic falls within the acceptable limit, then the inspection has an error. The simulator will record it as type I error. Then the part will be declared as a scrap. If the inspected value

and characteristic value fit together, then the inspection was done correctly. The part will be directly declared as a scrap. Before the simulator dispose the scrap parts out of the model, information on cost and time will be collected.

3.2.4 Sampling modules

The next four sampling modules are used to insert the sampling inspection into the model. The two options for sampling inspection are continuous and lot-by-lot. Each sampling inspection needs two modules. The front module should be placed before the inspection process. It is used in order for the model to take the samples from the production. The back module should be placed after the inspection process in order to signal the result of the inspection.

3.2.4.1 Continuous sampling inspection modules

The continuous sampling inspection modules are based on Dodge's AOQL plan for continuous production (CSP-1) /Dodge47/. The application of this plan aims for continuous production, since the formation of inspection lots for lot-by-lot acceptance is impractical and costly. The following explains the procedure of CSP-1.

1. At the outset, inspect 100% of the units consecutively as produced and continue such inspection until i units in succession are found clear of defects.
2. When i units in succession are found clear of defects, discontinue 100% inspection, and inspect only a fraction f of the units, selecting individual sample units one at a time from the flow of product, in such a manner as to assure an unbiased sample.
3. If a sample unit is found defective, revert immediately to a 100% inspection of succeeding units and continue until again i units in succession are found clear of defects, as in paragraph 1.

Therefore, the required values for "Sampling – Continuous (Front)" module are the number of units for 100% inspection (i) and the number of units for fraction inspection. The number of units for 100% inspection or the inspected fraction can be obtained corresponding to any desired average outgoing quality limit (AOQL). The necessary information for the selection of such a plan for any desired AOQL is given in Appendix 1.

As an example, suppose the desired AOQL is 2% and it is desired to establish a plan that calls for inspection of one piece out of every 20 pieces from the conveyor belt. Then the fraction inspected (f) is 1/20 or 5%. From Appendix 1, the value of i corresponding to an f of 5% on the curve of an AOQL of 2% is 76.

Therefore, the number of units for 100% inspection is 76 and the number of units for fraction inspection is equal to 20.

There are two exit arrows in Sampling – Continuous (Front) module (Figure 3.22). The upper one is the exit point to the next production process while the lower one is the exit point to the inspection process.

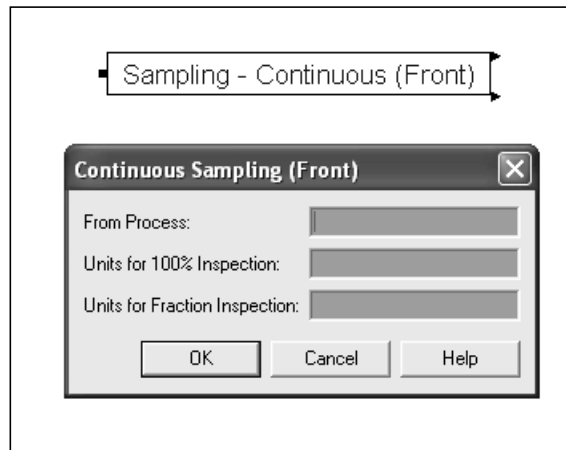


Figure 3.22: Sampling – Continuous (Front) module user view and dialog

The logic behind the “Sampling – Continuous (Front)” module is illustrated in Figure 3.23. Once the part enters the module, the simulator will first check the latest status if the 100% inspection or fraction inspection is used.

Status is 100% inspection: The simulator counts the number of the parts that has been sent to inspection. If the number of the parts that has been sent to inspection reaches i units, then the fraction inspection will start. And the status will be set to fraction inspection. The number of parts that has been sent to inspection will be set to zero before sending the part to inspection. If the number of the inspection part has not reached i unit, the simulator will continue the 100% inspection and send the part to the inspection process.

Status is fraction inspection: The simulator counts the number of the parts that has been sent to next production process. If the number of the parts that has been sent to the production reaches f units, then that part will be sent to inspection and the number of production part will be set to zero. If the number of the parts that has been sent to the production has not yet reached f units, the module will continue sending the part to the production without inspecting.

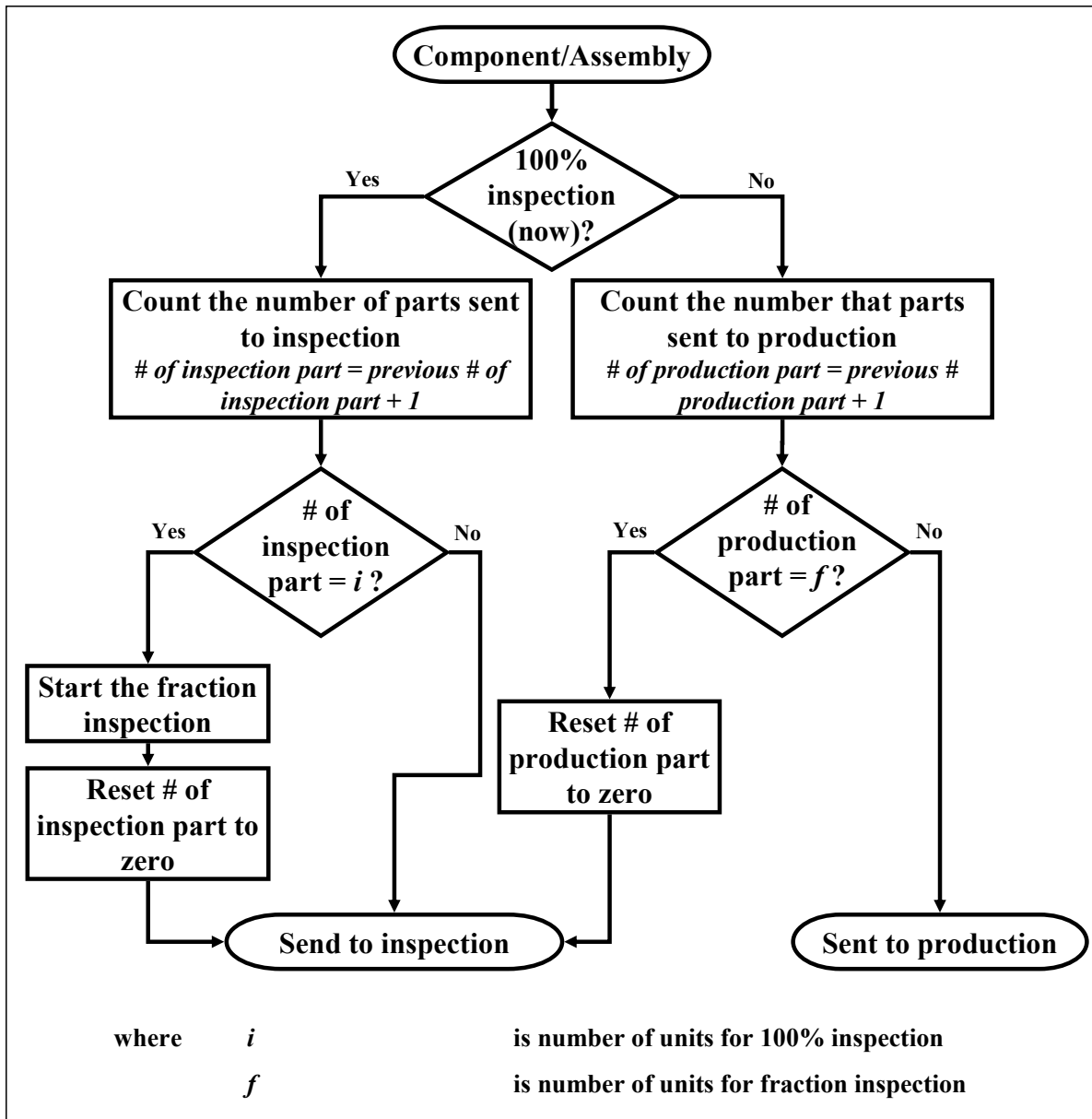


Figure 3.23: Sampling – Continuous (Front) module logic

After the inspection process, another module called “Sampling – Continuous (Back)” module is needed to signal back the result of the inspection. The result of the inspection tells when the fraction inspection should be changed back to 100% inspection. The condition here is that when a sample unit is found defective, the simulator should revert immediately to a 100% inspection.

The name of the process which produces the sampled parts is also required in order to retrieve the number of produced parts. In the “Sampling – Continuous (Back)” module, the user must specify the characteristic type of produced part. If the characteristic type is attributive, policy for nonconformity must be indicated.

If the characteristic type is variable, three entry points and three exit points will show up for this module. The upper most entry and exit points are for conformities. The middle entry and

exit points are for rework parts. Lastly, the lower most entry and exit points are for scraps. If the characteristic type is attribute, the entry and exit point for either rework or scrap parts will be disabled. Only two entry points and two exit points will show up. If the policy of nonconformities is rework, the entry or exit point for scraps will not show up.

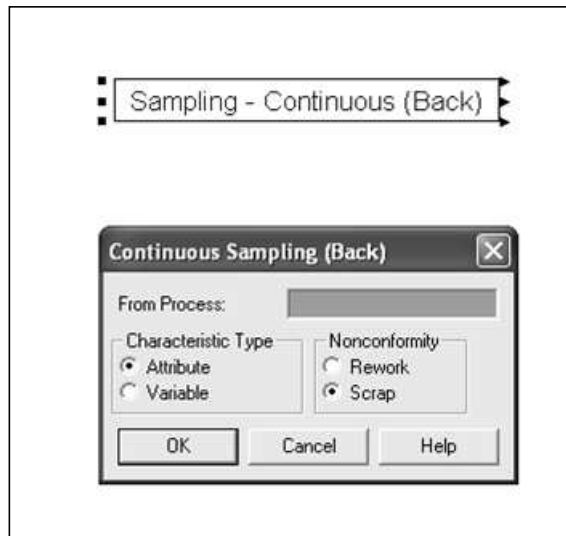


Figure 3.24: Sampling – Continuous (Back) user view and dialog

The logic of this module, which is shown in Figure 3.25, is simple. If the part that coming out from the inspection process is rework or scrap part, the simulator will send the signal to the “Sample – Continuous (Front)” module to change the inspection from fraction inspection to 100% inspection. The status of inspection will be set to 100% inspection.

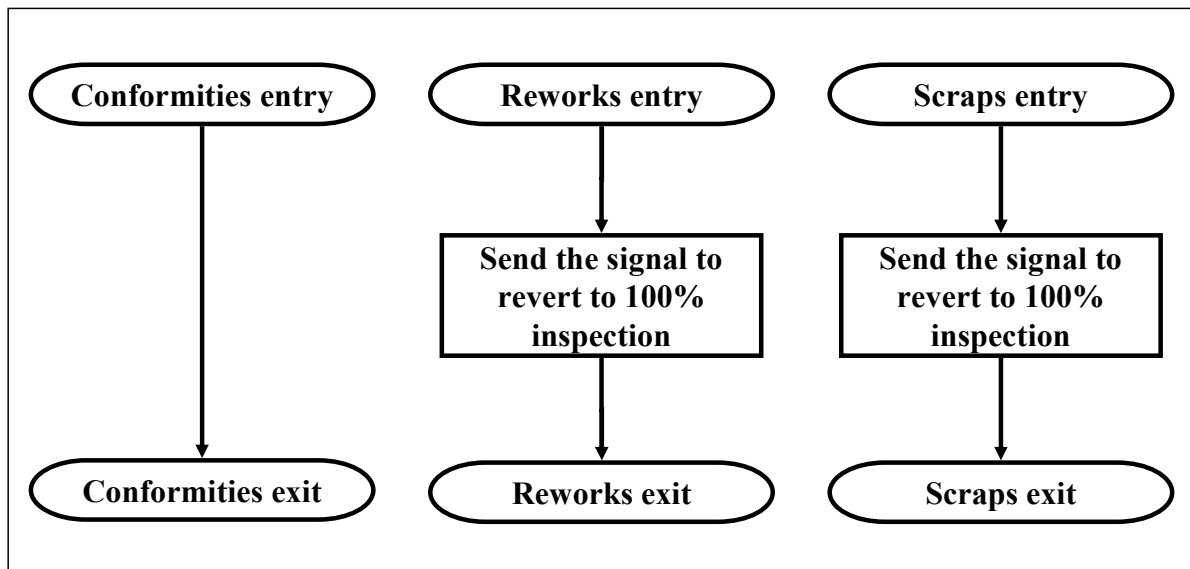


Figure 3.25: Sampling – Continuous (Back) module logic

3.2.4.2 Lot-by-Lot sampling inspection modules

The lot-by-lot sampling inspection modules were built according to a single sampling scheme. In single sampling plans, the decision to accept or reject a lot is based on the results of inspection of a single group of specimens drawn from the lot. Any single sampling plan requires that three numbers are specified. One is the number of parts N in the lot from which the sample is to be drawn. The second is the number of parts n in the random sample drawn from the lot. The third is the acceptance number c . This acceptance number is the maximum allowable number of defective parts in the sample. More than c defectives will cause rejection of the lot. Therefore, the rejection number, which will be used in one of these modules, is equal to acceptance number + 1.

In the “Sampling – Lot-By-Lot (Front)” module, only three fields of information are required. The needed information is the name of process that produce the sampled parts, lot size (N), and sample size (n).

The two exit points in this module (Figure 3.26) are the same as in “Sampling – Continuous (Front)” module. The upper one is the exit point to the next production process while the lower one is the exit point to the inspection process.

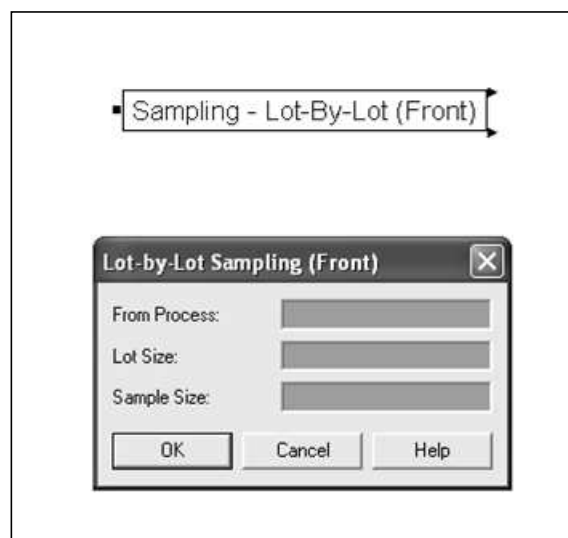


Figure 3.26: Sampling – Lot-By-Lot (Front) user view and dialog

The logic for the “Sampling – Lot-By-Lot (Front)” module is shown in Figure 3.27. The parts which enter this module will be gathered until size is equal to lot size (N). Then they will be separated into two groups. The first group or the samples is the one going to the inspection. The amount of parts in this group is equal to sample size (n). The rest belongs to the second group.

Before the samples proceed to inspection process, it has to be given the lot number and marked that it is a sampled part. The samples will be waited for 0.01 minute. This is because the model has to be updated with the “lot number” variable by the second group (non-sampled parts) before assigning the lot number value to the samples. With this lot number, the simulator is able to trace back the inspection result of the specified lot number.

The second group is also assigned the lot number, which is the same lot number as the first group. Then it will wait for the inspection result of the samples. This inspection result will be sent from “Sampling – Lot-By-Lot (Back)” module. If the inspection result is equal to zero, it means that the lot is accepted. The second group will be sent to the production together with the samples. If the inspection result is equal to one, it means that the lot is rejected. All parts in this lot will be sent to inspection process.

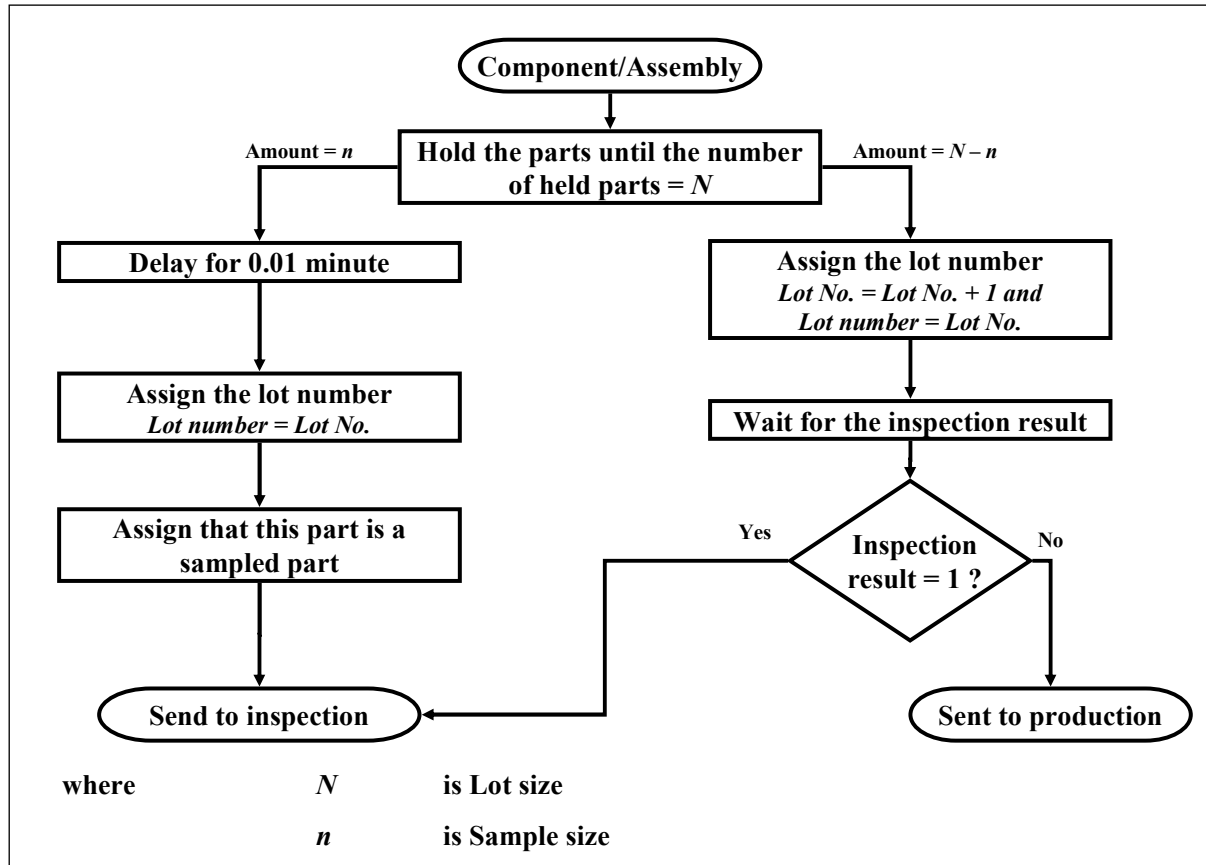


Figure 3.27: Sampling – Lot-By-Lot (Front) module logic

“Sampling – Lot-By-Lot (Back)” module, which is shown in Figure 3.28, is needed after the inspection process in order to signal back the result of the inspection. The result decides on the action to be done with the parts that are waiting at the “Sampling – Lot-By-Lot (Front)” module. Therefore, the information that is needed here must lead to the decision on the lot. This required information is lot size (N), sample size (n) and rejection number ($c+1$).

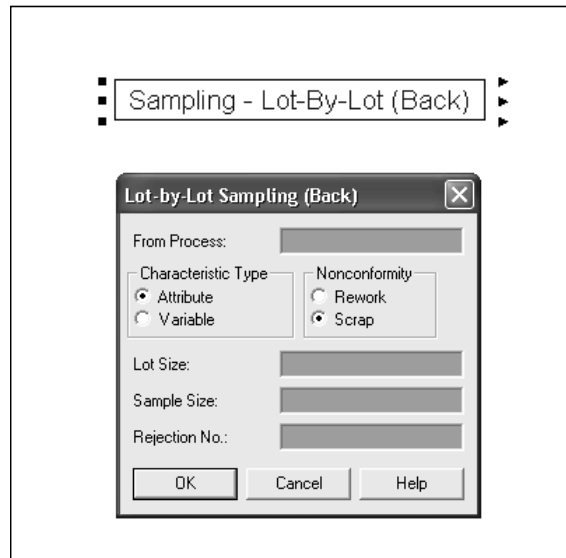


Figure 3.28: Sampling – Lot-By-Lot (Back) user view and dialog

Moreover, the name of the process which produces the sampled parts is also required in order to retrieve the number of produced parts. If the characteristic type is attributive, policy for nonconformity must be indicated.

If the characteristic type is variable, three entry points and three exit points will show up for this module. The upper most entry and exit points are for conformities. The middle entry and exit points are for rework parts. Lastly, the lower most entry and exit points are for scraps. If the characteristic type is attribute, the entry and exit point for either rework or scrap parts will be disabled. Only two entry points and two exit points will show up. If the policy of nonconformities is rework, the entry or exit point for scraps will not show up.

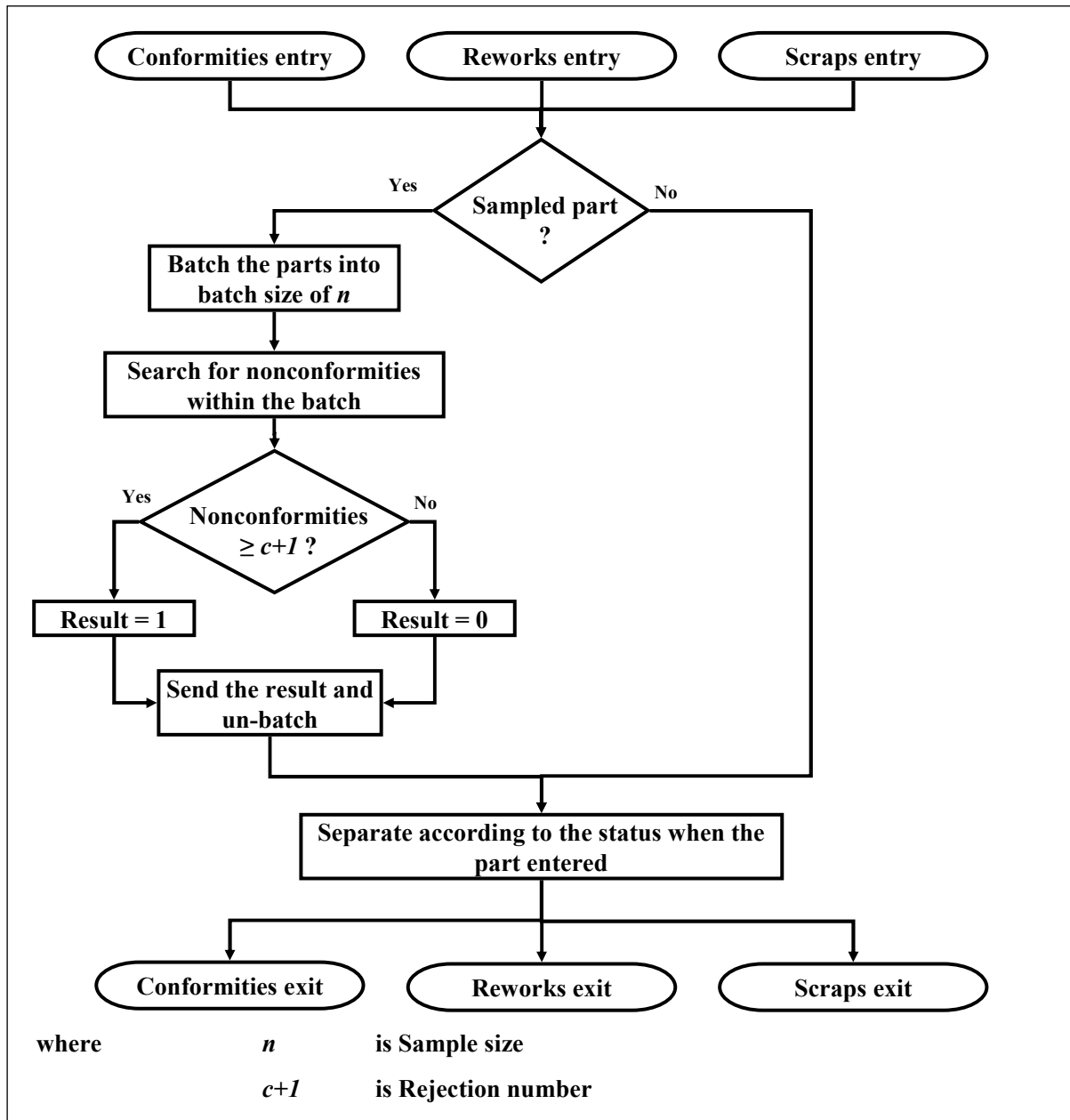


Figure 3.29: Sampling – Lot-By-Lot (Back) module logic

Figure 3.29 shows how this module functions. When the parts enter the module it will be checked if it is a sampled part. If it is not a sampled part, it will exit the module. If it is a sampled part, the part will be collected together as a batch until the batch size is equal to the sample size (n). The batch is searched for nonconformities and the number of nonconformities will be compared with the rejection number ($c+1$). If the number of nonconformities in a batch is equal to or more than the rejection number ($c+1$), the result value is set to one and the lot will be rejected. Otherwise, the result value is set to zero and the lot will be accepted. Afterwards, the part will be separated from the batch and exit the module.

3.2.5 Assembly logic module

This last module is used to combine the components into an assembly. The user has to assign assembly name, amount of component types and components, as well as the assembly details. The assembly details include the component name and the quantity of the component in one assembly. This module should be placed before the product is assembled or in another words it should be placed before the process module for the assembly.

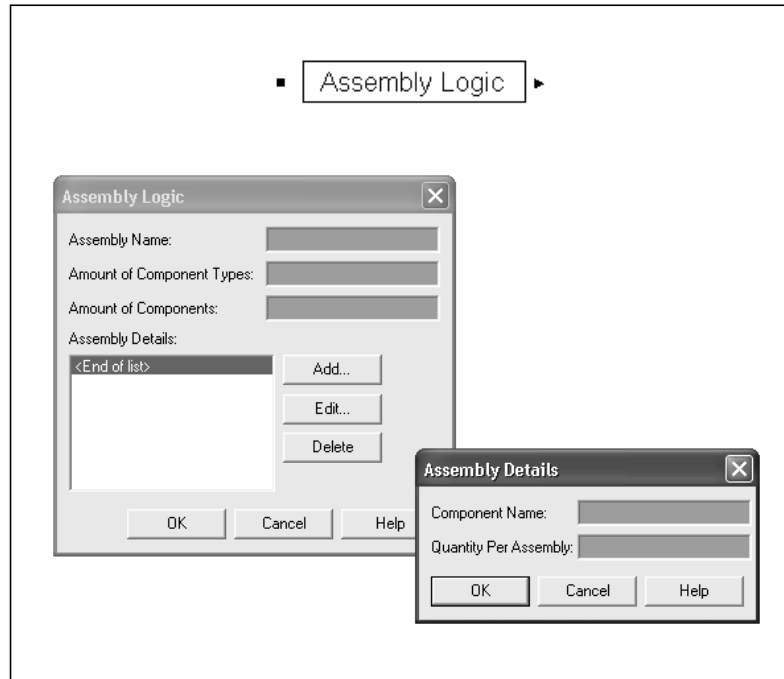


Figure 3.30: Assembly Logic user view and dialog

Figure 3.31 illustrates the logic of “Assembly Logic” module which is explained in the details in the following paragraph.

When the component enters this module, it will be given the influence factor which based on the equation 3.3. The component will wait in a queue until all the required components have arrived at this module, and then the simulator calculates the combined influence factor for all components one by one. The costs that all components possess are transferred to costs for the assembly. These costs include value added cost, non-value added cost, wait cost, transfer cost, and other cost.

The simulator also records the flow time for all components before being assembled. After the assembly is created, it will be assigned with the influence factor for assembly. The influence factor for the assembly is calculated based on the equation 3.4. Furthermore, the simulator gives the assembly the name and the cost, which has been transferred from the components’ costs. Towards the end of the module, the combined influence factor must be reset to one as well as the initial value for product of distance ratio must be set as one to this assembly.

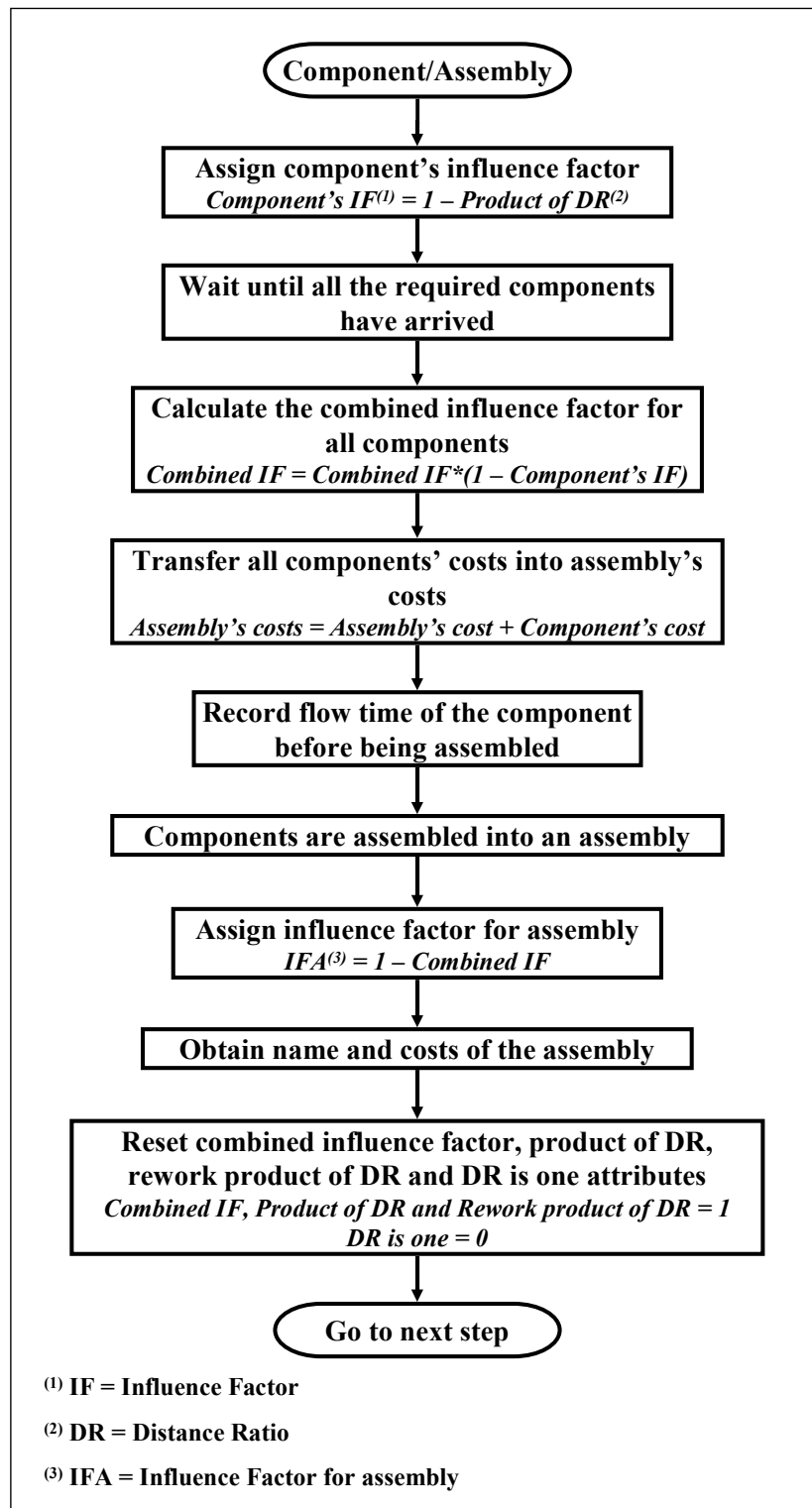


Figure 3.31: Assembly Logic module logic

3.3 MODELLING EXAMPLE

The simulation model can easily be built with the SixSigma template and other Arena's templates. The user can build the model by dragging and dropping the required modules into the modelling space, fill in the necessary information, and connect the modules together in the same order as the process flow. A simple example of how to model in Arena is illustrated in Figure 3.32.

The example shows the manufacturing and inspection of bolts and nuts and the assembly process of one bolt and two nuts. Bolts and nuts enter the simulation model by the "Create 1" and "Create 2" respectively. In create module, which is from Arena's template, the part name and arrival interval can be stated. Production sequences of bolts and nuts are different at the first process step. The first process step for manufacturing bolts is the turning process while for manufacturing nuts is the drilling process. Then both bolts and nuts have to pass through a surface polishing process before being assembled at the assembly process. In this example, an inspection is done after every process. Each process step is modelled under one submodel in order to reduce the complexity; for example, the turning process is modelled under a submodel called "Turning & Inspection Process". The detailed modelling of "Turning & Inspection Process" is presented in Figure 3.33.

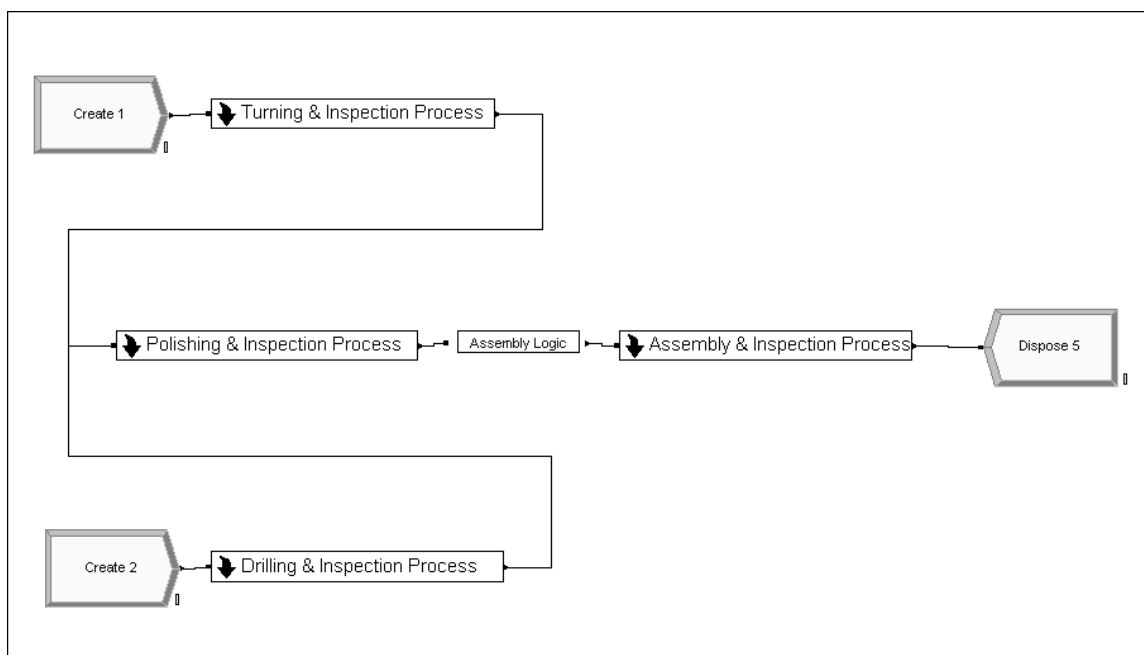


Figure 3.32: Modelling example

When the bolts enter "Turning & Inspection Process" submodel, they are transferred directly to a turning machine, which produces "Outer Diameter_Bolt" as a quality characteristic. After the characteristic is produced, the bolts are being sampled by continuous sampling plan. Those which must not be inspected go to the next production step which is in this example case is the surface polishing process. Those which must be inspected are sent to the bolt's outer diameter inspection process.

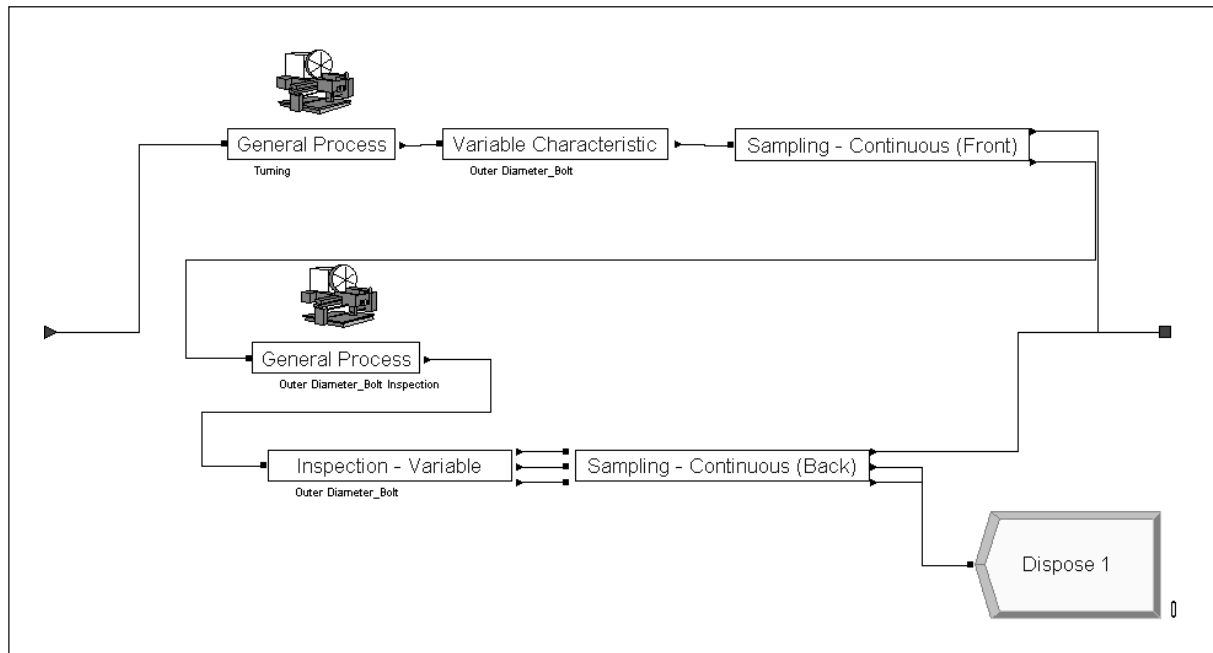


Figure 3.33: “Turning & Inspection Process” submodel

At the bolt’s outer diameter inspection process, the bolts go through the inspection process prior to getting the inspected value of bolt’s outer diameter. The “Sampling – Continuous (Back)” module is placed after the “Inspection –Variable” with the purpose of providing the inspection result to the production. If a sample unit is found defective, 100% inspection is performed immediately instead of the fraction inspection. It is assumed that there is no possibility for rework in this example. Therefore, the parts, which fall outside the specification limit, are scrap and they are disposed from the simulation model. The conforming parts are sent to the surface polishing process.

The other submodels in the example are modelled in a similar way as “Turning & Inspection Process” submodel. Therefore, they are not described in detail.

3.4 VERIFICATION AND VALIDATION OF SIXSIGMA SIMULATOR

Once the SixSigma template with the model for characteristic values and the quality effect in assembly process was developed, the model of manufacturing and assembly process was built in ARENA® simulation software in order to test the function of the SixSigma simulator. The simulator was verified and validated before it can be used to investigate and evaluate the inspection strategies in the real situation.

The verification was done to ensure that the model is built according to specifications and to eliminate errors in the structure, algorithm, and computer implementation of the model /Kelton98/. It was done simultaneously with the model building. There are many techniques which are used, for instance, debugging, tracing through detail logic, or verifying using animation.

Validation is the process of ensuring that the model is a good representation of reality /Evans98/. The preliminary validation of the simulator was done to test the quality effects model of manufacturing process on assembly process. This validation will be discussed in this chapter. The final validation was done together with a pilot company in order to mimic the application of the simulator in the real situation. It will be presented separately in the next chapter.

A simple example of an assembly, which consists of two Component 1 and one Component 2, was created in order to use in the model validation. Component 1 and 2 are randomly created with the exponential inter-arrival time of 15 and 30 minutes respectively. The specifications of components and assembly are shown in Table 3.1. It is assumed that the incoming raw materials are defect-free and the transportation cost is neglected. Each simulation runs for 10 replications and each replication contains 80,000 minutes with 30,000 minutes warm-up period.

	Target value (mm.)	Specifications (mm.)			
		MIN	LSL	USL	MAX
Component 1	10	6.5	7	13	13.5
Component 2	12	8.5	9	15	15.5
Assembly	2	0.75	1	3	3.25

Table 3.1: Specifications of components and assembly

In the model, there are three manufacturing processes, one assembly process, four inspection processes, and four rework processes. The information related to each process is demonstrated in Table 3.2.

Process	Characteristic		Processing time (min)
	Type	Name	
Turning	Variable	Outer diameter	NORM(15,1)
Milling	Variable	Inner diameter	NORM(15,1)
Polishing	Attribute	Surface	NORM(15,1)
Assembly	Variable	Assembly	NORM(15,1)
Outer diameter inspection	Variable	-	NORM(5,0.2)
Inner diameter inspection	Variable	-	NORM(5,0.2)
Surface inspection	Attribute	-	NORM(5,0.2)
Assembly inspection	Variable	-	NORM(5,0.2)
Outer diameter rework	Variable	Outer diameter	TRIA(2,5,8)
Inner diameter rework	Variable	Inner diameter	TRIA(2,5,8)
Surface rework	Attribute	Surface	TRIA(2,5,8)
Assembly rework	Variable	Assembly	TRIA(2,5,8)

Note: NORM(μ, σ) = Normal distribution (mean, standard deviation)

TRIA(a, m, b) = Triangular distribution (minimum, mode, maximum)

Table 3.2: Process details

The costs in the simulation results are calculated based on the holding cost. Each part has the same holding cost of 10 Euro per hour. This holding cost rate is used to calculate the value added cost, non-value added cost, and waiting cost. Any time that the product or component spends in the system waiting or in any type of process; it will incur costs based on its current holding cost rate. Additionally from the in-process cost, the raw material cost of both components is fixed at 10 Euro per unit.

The validation was done with 16 experiments. The routing sequences of components and assembly for each experiment are shown in Table 3.3.

	Experiment no.	Step 1	Step 2	Step 3	Step 4
Component 1	1 - 13	Turning	Assembly		
Component 2	1 - 13	Milling	Assembly		
Assembly	1 - 13		Assembly	Exit	
Component 1	14 - 16	Turning	Polishing	Assembly	
Component 2	14 - 16	Milling	Polishing	Assembly	
Assembly	14 - 16			Assembly	Exit

Table 3.3: Routing sequence

Experiments were done on different manufacturing process capability levels and different inspection process capability levels. The levels which are used in all experiments are summarised in Table 3.4.

Level	Production process capability			
	Turning	Milling	Polishing	Assembly
1	$C_p = 0.7$ ($\sigma = 1.429$)	$C_p = 0.7$ ($\sigma = 1.429$)	97% conformity	$C_p = 1.33$ ($\sigma = 0.251$)
2	$C_p = 0.95$ ($\sigma = 1.053$)	$C_p = 0.95$ ($\sigma = 1.053$)	-	-
3	$C_p = 1.35$ ($\sigma = 0.741$)	$C_p = 1.35$ ($\sigma = 0.741$)	-	-
Level	Inspection process capability			
	Outer diameter	Inner diameter	Surface	Assembly
1	$u = 0.5$	$u = 0.5$	99.99% accuracy	$u = 0.005$
2	$u = 0.3$	$u = 0.3$	-	-
3	$u = 0.05$	$u = 0.05$	-	-
4	$u = 0.005$	$u = 0.005$	-	-

Table 3.4: Process capability levels

The production process capability for turning, milling, and assembly are represented by the capability index while polishing process capability is shown in the form of conformity rate. The capability index can be calculated by the following equation:

$$C_p = (USL - LSL)/6\sigma \quad (3.5)$$

where USL is upper specification limit
 LSL is lower specification limit

The inspection process capability for turning, milling and assembly are represented by the uncertainty (u) whereas the polishing process capability is shown in the form of accuracy rate. The capabilities of the outer diameter rework process, inner diameter rework process, and assembly rework process is directly proportional to the capabilities of the turning process, milling process, and assembly process respectively. But the rework process conformity of the polishing process is set to 99.5%.

The list of experiments is illustrated in Table 3.5. The capability levels of each process, inspection extent as well as the important factor are included in the table. The capability levels are based on the levels in Table 3.4.

The single sampling plans that are used in the experiment No. 12 and No. 13 are derived from the acceptable quality level (AQL) of 10 and 2.5 respectively.

Experiment No.	Capability level								Inspection extent				Important factor
	Turning process	Milling process	Surface process	Assembly process	Outer diameter inspection	Inner diameter inspection	Surface inspection	Assembly inspection	Outer diameter inspection	Inner diameter inspection	Surface inspection	Assembly inspection	
1	2	2	-	1	4	4	-	1	100%	100%	-	100%	0.5
2	3	3	-	1	4	4	-	1	100%	100%	-	100%	0.5
3	3	3	-	1	3	3	-	1	100%	100%	-	100%	0.5
4	1	1	-	1	4	4	-	1	100%	100%	-	100%	0.5
5	1	1	-	1	3	3	-	1	100%	100%	-	100%	0.5
6	1	1	-	1	-	-	-	1	-	-	-	100%	0.5
7	3	3	-	1	-	-	-	1	-	-	-	100%	0.5
8	1	1	-	1	2	2	-	1	100%	100%	-	100%	0.5
9	1	1	-	1	1	1	-	1	100%	100%	-	100%	0.5
10	1	1	-	1	1	1	-	1	100%	100%	-	100%	1
11	1	1	-	1	1	1	-	1	100%	100%	-	100%	0.8
12	1	1	-	1	4	4	-	1	20/5/2	20/5/2	-	100%	1
13	1	1	-	1	4	4	-	1	20/5/1	20/5/1	-	100%	1
14	1	1	1	1	4	4	1	1	-	-	-	100%	1
15	1	1	1	1	4	4	1	1	-	-	100%	100%	1
16	1	1	1	1	4	4	1	1	100%	100%	100%	100%	1

Note: $N/n/c+1$ is single sampling plan with lot size = N , sample size = n , rejection no. = $c+1$

Table 3.5: List of experiments

In the first part, the comparisons were done on different manufacturing process capabilities (C_p), different inspection equipment uncertainties (u) and different importance factors in

order to investigate if the generated model is able to simulate the effect of manufacturing processes on assembly process or not and how they effect on the assembly process. Then, the simulation results are compared with the logical trend. The results are shown in the Figure 3.34.

Logically, the higher manufacturing process capability causes the fewer defective parts, lower failure costs, such as scrap and rework cost, lower inspection cost, and lower decision errors in both manufacturing and assembly process. The results match the logical trend apart from the assembly scrap and rework cost. As the manufacturing process capability increases, the assembly scrap and rework cost can decrease or stay unchanged depending on the inspection equipment uncertainty. If the inspection equipment has low uncertainty, then the bad components are already detected in the inspection process. The quality of the assemblies is not much affected.

Comparison area	Mfg. process capability (Cp)	Inspection equipment uncertainty (u)	Important factor
	Cp = 0.7 ↓	u = 0.5 ↓	Imp. factor = 0.5 ↓
Type of costs	Cp = 1.35	u = 0.005	Imp. factor = 1
Production cost (based on flow time)	→	↑	→
Mfg. scrap and rework cost	↓	→	→
Ass'y scrap and rework cost	↓ / →	↓	↑
Inspection cost	↓	↑	→
No. of decision errors	↓	↓	→

Figure 3.34: Simulation results for validation


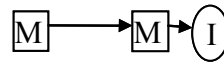

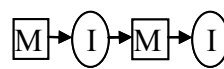
















When the inspection equipment uncertainty decreases, scrap and rework cost and decision errors of both processes should decrease. Flow time and inspection cost increase when the inspection uncertainty decreases. That is because more defective parts can be detected with the lower inspection uncertainty and these defectives have to be reworked thus the flow time and inspection cost increase. The comparison result shows that the manufacturing scrap and

rework cost remains no different since many type I decision errors occur when the inspection equipment uncertainty is high.

The only effect, which occurs from the variation of importance factor, is the assembly scrap and rework cost. The assembly scrap and rework cost raises when the important factor increases.

With this kind of information the company can decide on which tolerance for the manufacturing and assembly process that they should use in order to achieve the economical result.

The second part is the comparison of different inspection strategy aspects. The chosen aspects in this study are inspection point, inspection extent, and inspection equipment. The experiments were done by varying the aspects of inspection strategies then comparing the results with respect to quality, cost and time. Finally, the results can be used to investigate the fluctuation of the production performance according to these changes. The comparison is shown in the Figure 3.35.

Comparison area	Inspection equipment uncertainty (u)	Inspection point	Inspection extent
Type of costs	u = 0.5  u = 0.005	  	Sampling inspection  100% inspection
Production cost (based on flow time)			
Mfg. scrap and rework cost			
Ass'y scrap and rework cost			
Inspection cost			
No. of decision errors			

M = manufacturing process, I = inspection process

Figure 3.35: Comparison between different inspection strategies

The comparison between combined inspection and the inspection after every process shows that the flow time and inspection cost are lower for the combined inspection since the queuing can be reduced. However, the scrap and rework cost are higher since more value is already added to the defective part.

100% inspection causes higher manufacturing scrap and rework cost and also inspection cost. On the other hand, it also produces lower assembly scrap and rework cost since the defective components are already sorted out in manufacturing process. The higher inspection extent also results in the higher amount of decision errors. The simulation result shows that flow time does not depend on inspection extent.

The result for different inspection equipment uncertainty is not discussed in this part as it was already discussed in the first part of the discussion.

These results prove that the mathematical model, which assigns an influence factor for each assembly part according to the quality and importance of its manufactured components, was successfully developed and validated as well as the SixSigma template. The result also shows the application of the template in improving the assembly process by tolerance planning and inspection planning.

After the verification and preliminary validation, the SixSigma template should be validated by using the actual data from the pilot company. The historical data can be input and the result can be compared with the historical data. This next validation step will be shown in the next chapter.

4. IMPLEMENTATION IN A PILOT COMPANY

The simulator was validated in the pilot company. This chapter shows how the simulator was implemented in the pilot company as well as the obtained result.

4.1 COMPANY BACKGROUND

Harms & Wende GmbH & Co. KG was founded more than 60 years ago. The company is based in Hamburg, Germany. They have 18 business partners worldwide. Their expertise is in the area of resistance welding, friction welding and quality control of all welding processes. Today they supply various types of products range from complex automated friction welding machine to in-line process control system with integrated database and visualisation /Harms05/.

This company suits to be the pilot company for the simulator validation since they have various products which consist of several components. Moreover, they have done some data collection and analysis on the quality of the components and assemblies which can be used as an input and as an outcome to validate the simulator.

Yield rate has been used in order to calculate the quality of their products. The yield rate of the final product has to be partly estimated from the quality of the components. However, it is quite hard to estimate the quality of the final product which consists of several components. Therefore, they would like to use simulation as a tool to investigate the quality of the components and final assemblies.

4.2 MODEL CONCEPTUALISATION

In order to develop a model to validate the simulator, the concept of the model has to be created. Many things should be taken into consideration for example, data structure or constraints, the type of analysis to be performed, etc.

The scope of modelling for this case study is limited to one product, an inverter. The inverter consists of several components as shown in the bill of material in Figure 4.1.

The components which are presented at the bottom of the bill of material are the circuit boards. The simulation for this inverter does not include the two circuit boards (NIB1 and NEA1) which are optional for the end product. The complete product is illustrated in the Figure 4.2.

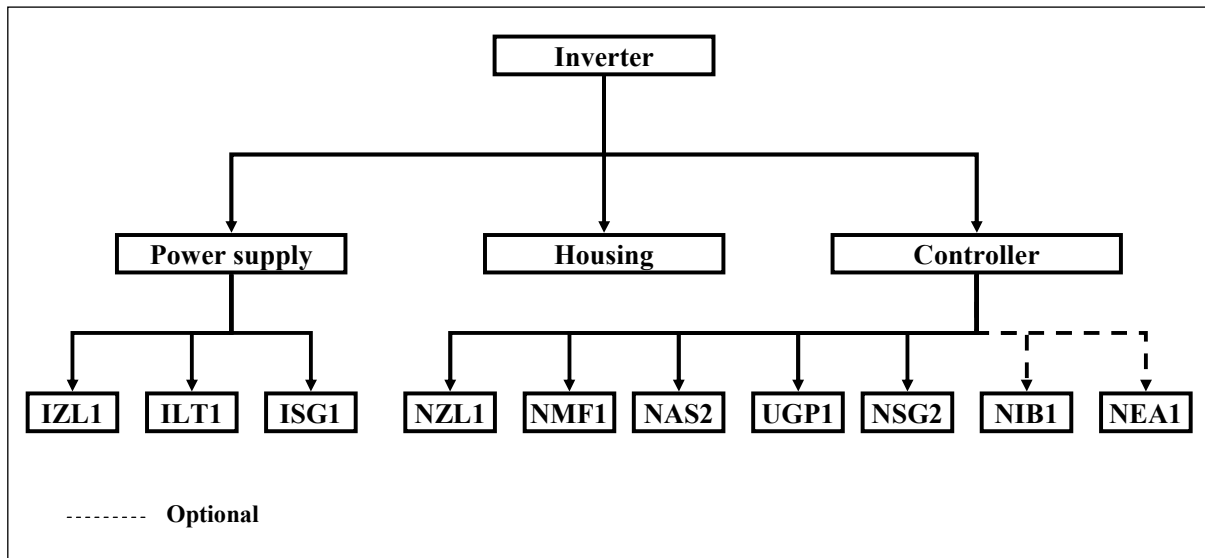


Figure 4.1: Inverter's bill of material

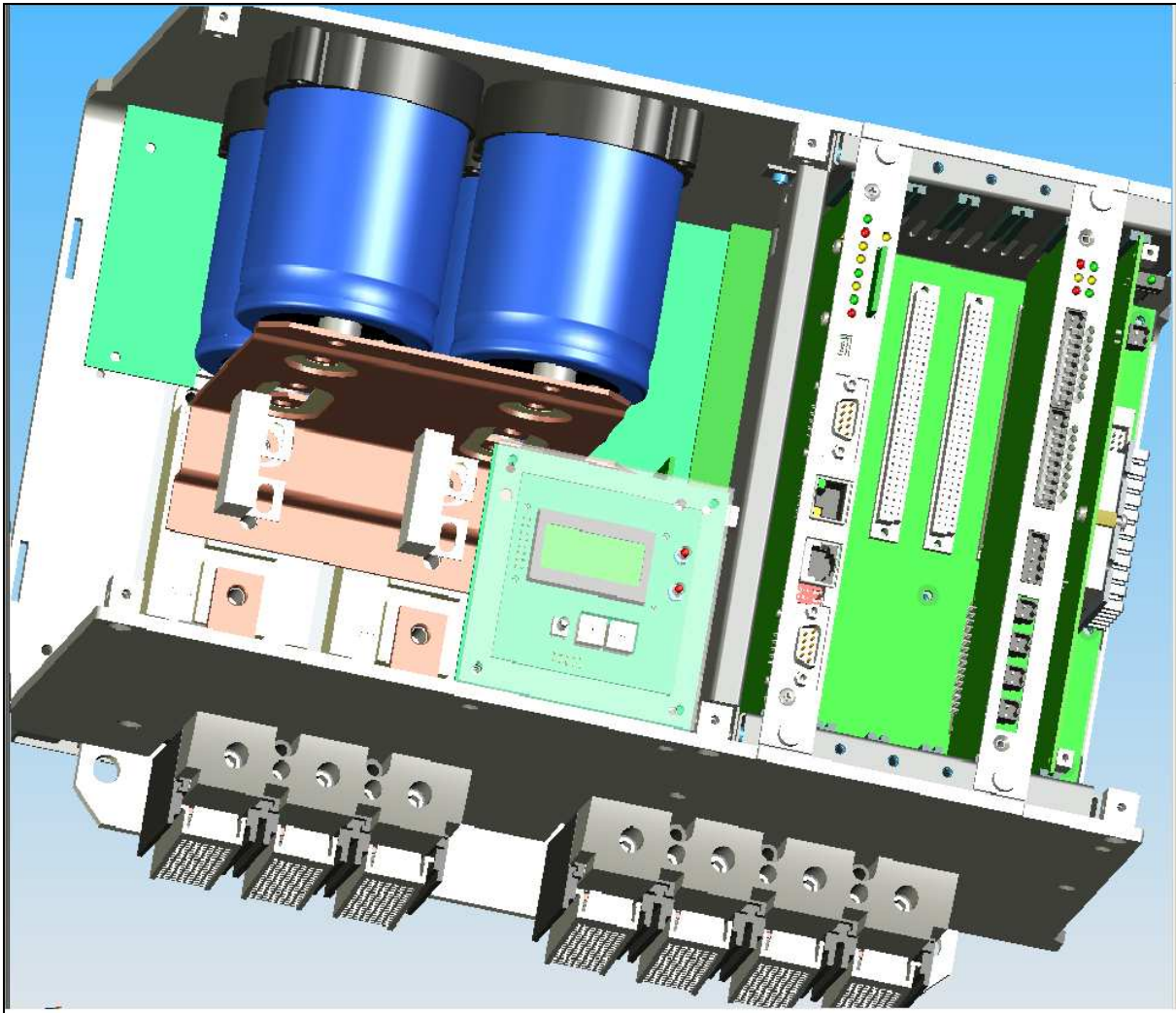


Figure 4.2: 3D-drawing of inverter

4.2.1 Circuit board

Before the circuit boards are assembled into the power supply or controller, they have to be processed according to the flow chart in Figure 4.3. The circuit boards are classified into two types; with front plate and without front plate. The front plates are attached to circuit boards after the programming process. The boards that are not equipped with front plate are NAS2 and ILT1. The inspection processes after the insertion processes and after programming process are optional. The company has the choice to make any of the inspections.

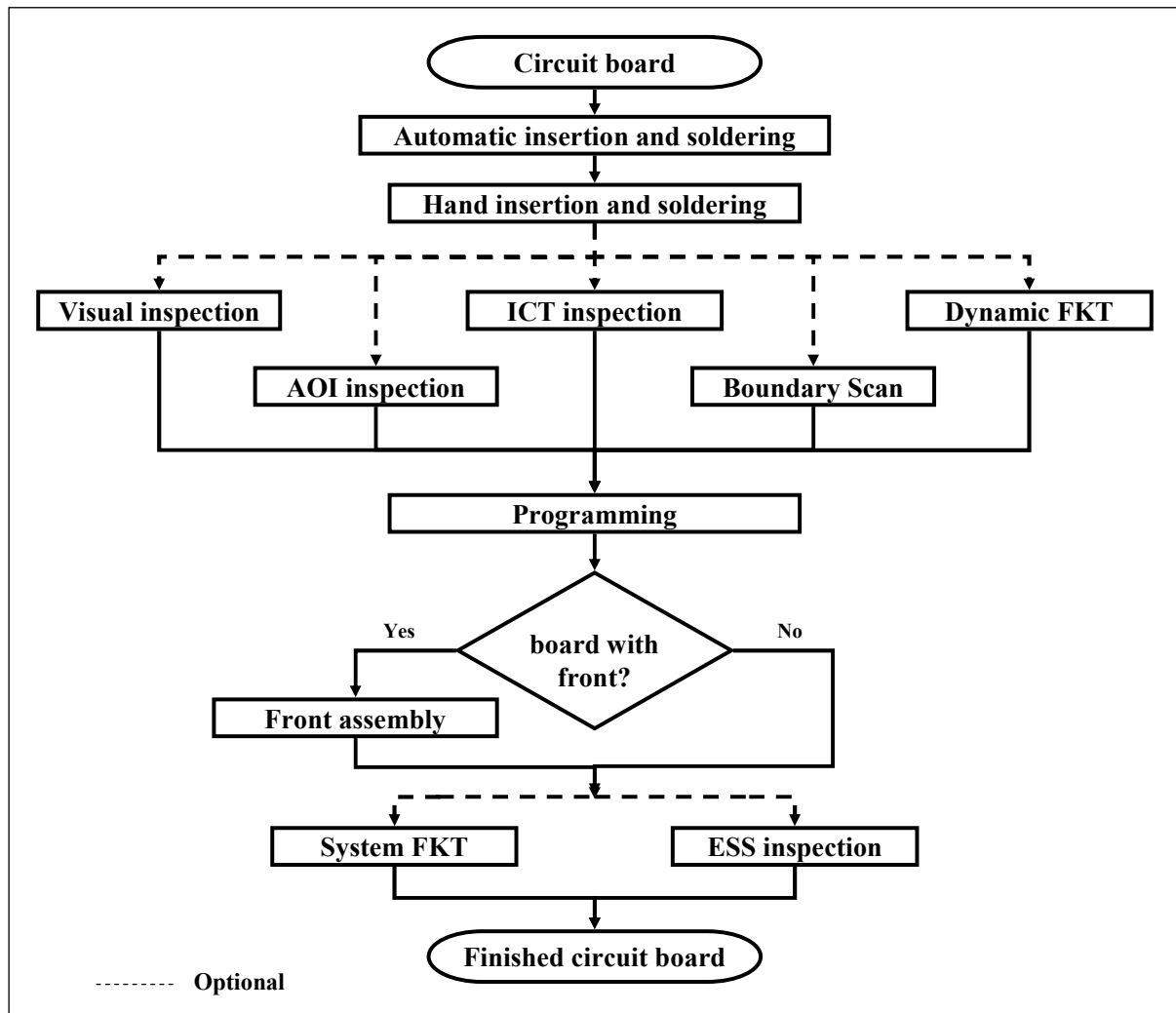


Figure 4.3: Processes for circuit board

4.2.2 Power supply, housing and controller

The three circuit boards are assembled into the power supply. Then the power supply will pass through the one or two inspection processes. It is also up to the company which inspection process should be conducted. After the power supply is inspected, it will be assembled with the housing before being assembled with the controller.

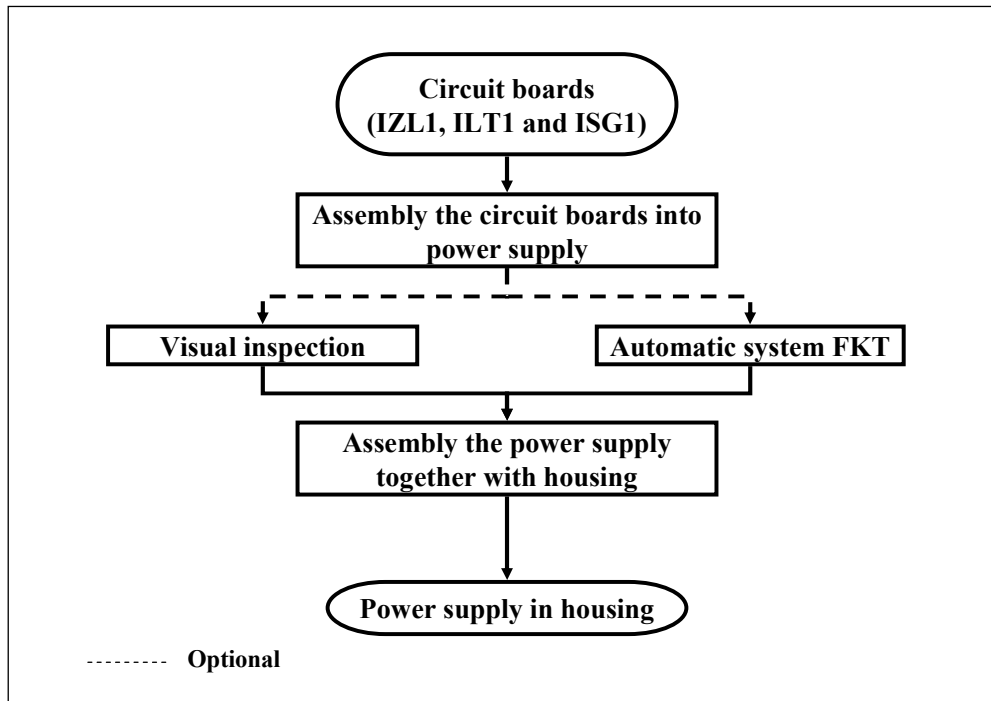


Figure 4.4: Processes for power supply and housing

4.2.3 Controller

In order to produce the inverter, five to seven circuit boards must be assembled together as a controller and put in to the housing which already contains the power supply. The finished inverter will be configured, and then it will be inspected. The inspection processes are also defined by the company. Figure 4.5 describes the processes for controller and inverter.

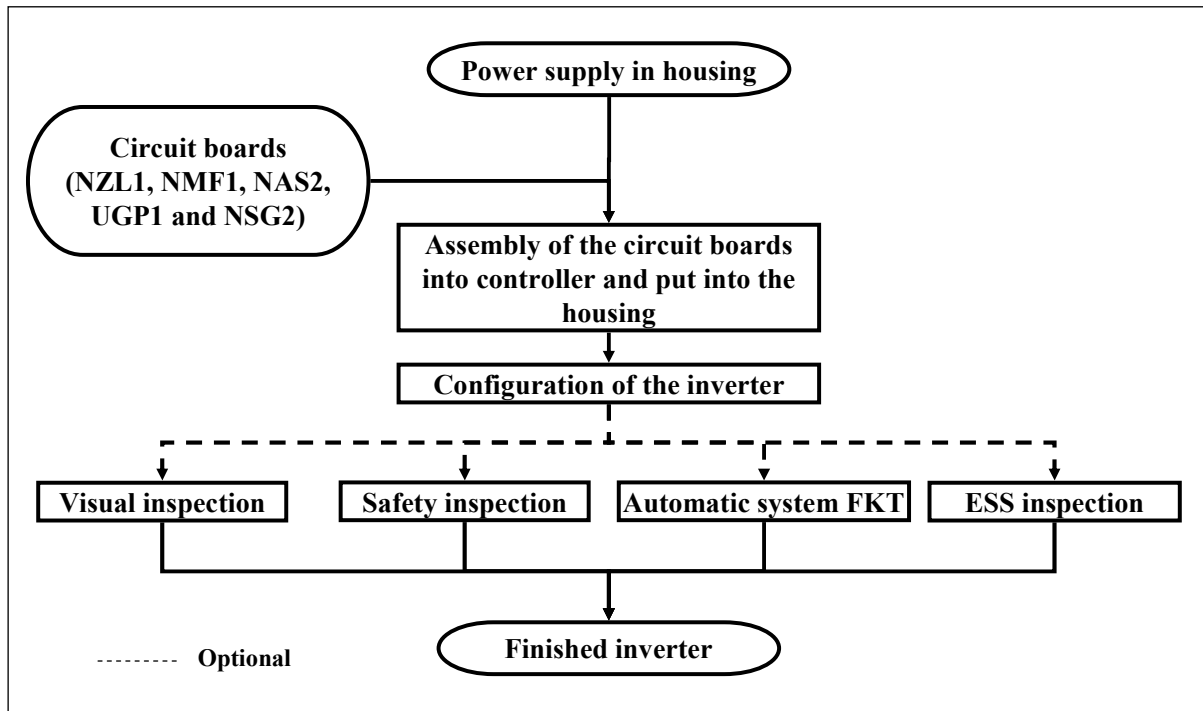


Figure 4.5: Processes for controller and inverter

4.3 LEVEL OF DETAIL AND ASSUMPTIONS

4.3.1 Level of detail

The model includes the production, inspection and rework processes of the inverter and its components. The following describes items, which are included and not included in the model.

- Processing time and setup time of each process are included in the model.
- Failure of each machine or equipment is not modelled.

4.3.2 Assumptions

The following list summarises the assumptions on which the simulation is based.

- Raw material is always available.
- Operators are always available and they are modelled in the same way as machine.
- Nonconformity is sent to rework processes right after it is detected at the inspection process.
- No nonconformity is produced at the rework process. All rework operations are completed in a satisfying way.
- Queue in front of each machine or operator have unlimited capacity.
- The transportation time between stations is fixed at one minute.

4.4 DATA COLLECTION

In line with the objectives of simulation, the input data and simulation model shall enable the investigation of the quality, time, and cost of producing the product. The input data is not only required to build the simulation model, it is also necessary for the model validation.

On top of the bill of material and the process flow, there are still some other required input data. These required input data will be shown here in this section.

4.4.1 Production schedule

In order to run a simulation model, the information that tells which products will be produced at what time is needed. In this case, there is only one finished product to be produced. The components arrive at the model at every 5500 minutes. This information is not based on historical data but it is set in a way that the entities in the model do not exceed the limited capacity of the software.

4.4.2 Processing and setup time

In this section, the processing and setup time will be described according to the type of the process.

4.4.2.1 Production processes

Automatic insertion setup	90	minutes
Automatic insertion and soldering	12	minutes
Hand insertion and soldering	33	minutes
Circuit board programming setup	20	minutes
Circuit board programming	2	minutes
Front assembly	2	minutes
Assembly of circuit boards into power supply	60	minutes
Assembly of power supply with housing	15	minutes
Assembly of circuit boards into controller and put into housing	15	minutes
Configuration of the inverter	15	minutes

4.4.2.2 Inspection processes

Visual – circuit board	3	minutes
AOI	2	minutes
ICT	2	minutes
Boundary scan	1	minute
Dynamic FKT	1	minute
System FKT	5	minutes
ESS – circuit board	10	minutes
Visual – power supply	10	minutes

Automatic system FKT – power supply	20	minutes
Visual – inverter	3	minutes
Safety	10	minutes
Automatic system FKT – inverter	20	minutes
ESS – inverter	10	minutes

4.4.2.3 Rework processes

The rework processes for the circuit board requires one minute whereas the processing times of the rework processes for the power supply, controller and inverter are 20 minutes.

4.4.3 Cost

The hourly costs of each process are listed below according to the process type. However, due to confidentiality, the cost shown here are not concrete values but only relative values.

4.4.3.1 Production processes

Automatic insertion setup	1.37
Automatic insertion and soldering	1.37
Hand insertion and soldering	1.39
Circuit board programming setup	1.18
Circuit board programming	1.18
Front assembly	1.37
Assembly of circuit boards into power supply	1.37
Assembly of power supply with housing	1.37
Assembly of circuit boards into controller and put into housing	1.37
Configuration of the inverter	1.37

4.4.3.2 Inspection processes

Visual – circuit board	1.18
AOI	1.18
ICT	1.18
Boundary scan	1.18
Dynamic FKT	1.18
System FKT	1.51
ESS – circuit board	1.51
Visual – power supply	1.51
Automatic system FKT – power supply	1.51
Visual – inverter	1.51
Safety	1.51
Automatic system FKT – inverter	1.51
ESS – inverter	1.51

4.4.3 Rework processes

All rework processes have hourly rate of 1.5 units.

4.4.4 Conformity rate

The conformity rates that used in the simulation are divided into different product according to different failure type. The name of the failure type is shown in German in order to avoid the misunderstanding which caused by translation. The conformity rates of each product are shown in Appendix 2.

4.4.5 Inspection accuracy

The information on inspection equipment's accuracy does not exist. However, there is information on the failure detection rate which can be used in this case. In the model, the inspection accuracy is assumed to be 100%. After the inspection process, the non-conformities are sent to the rework based on the failure detection rate. The rest of the non-conformities will be mixed with the conformity again which means that they cannot be detected by the inspection process.

The failure detection rates are also shown in Appendix 2.

4.4.6 Importance factor

The importance factor is specified by the company. They rated the importance of each failure type in percentage. The importance factors of each failure type and each product are included in Appendix 2.

4.5 EXPERIMENTAL DESIGN AND RESULT ANALYSIS

Various experiments can be done on the simulation models. In order to examine the performance of the models and make comparisons, all models are subjected to the similar input conditions. The experiments are planned in order to validate the model and find the suitable inspection and tolerance planning for the production of inverter.

4.5.1 Experiment set no. 1: Validation on single component

Initially, the experimental runs started from one single circuit board. The function of simulator for modelling the manufacturing processes of single product is validated here. The main circuit board, which is NZL1, is chosen to be investigated.

The simulation was run with run length of 30000 hours. The circuit boards arrive into the system in a batch of 100 boards and with the arrival rate of 5500 minutes. The maximum arrival of the circuit boards is equal to 300 batches.

According to the company's policy, the inspection processes are classified into 3 groups. The first one consists of visual inspection and AOI, the second one consists of ICT, Boundary Scan and Dynamic FKT, and the third one consists of Sys-FKT and ESS. At least one inspection from each group must be conducted. Therefore, the experiment has been designed according to this constraint.

Nine inspection strategies were run in this experiment set. The process sequences are shown in Table 4.1.

	Automatic insertion and soldering	Hand insertion and soldering	Visual inspection	AOI	ICT	Boundary Scan	Dynamic FKT	Programming	Front assembly	Sys-FKT	ESS
Strategy 1	x	x	x		x			x	x	x	
Strategy 2	x	x		x	x			x	x	x	
Strategy 3	x	x	x	x	x			x	x	x	
Strategy 4	x	x	x			x		x	x	x	
Strategy 5	x	x	x				x	x	x	x	
Strategy 6	x	x	x		x	x	x	x	x	x	
Strategy 7	x	x	x		x			x	x		x
Strategy 8	x	x	x		x			x	x	x	x
Strategy 9	x	x	x	x	x	x	x	x	x	x	x

Table 4.1: Inspection strategies for NZL1

The results of the nine simulation scenarios are shown in Appendix 3. This result was compared with the company's existing yield calculation. The example of how the company calculates for the NZL1's yield rate is shown in Appendix 4.

The simulation result can be looked into two sections. The first section demonstrates the overall performances of the model which are the amount of produced units, undetected defects, and the costs. The costs that are considered here are value added cost such as production cost and non-value added cost such as inspection cost and rework cost. In this model, time is translated into costs. The results on undetected defects and cost are shown in Figure 4.6 and 4.7.

Based on the simulation result, the company can choose the strategy that gives the required quality level with the minimum costs. The decision depends on the weight that the company given on the three factors; quality, time and cost.

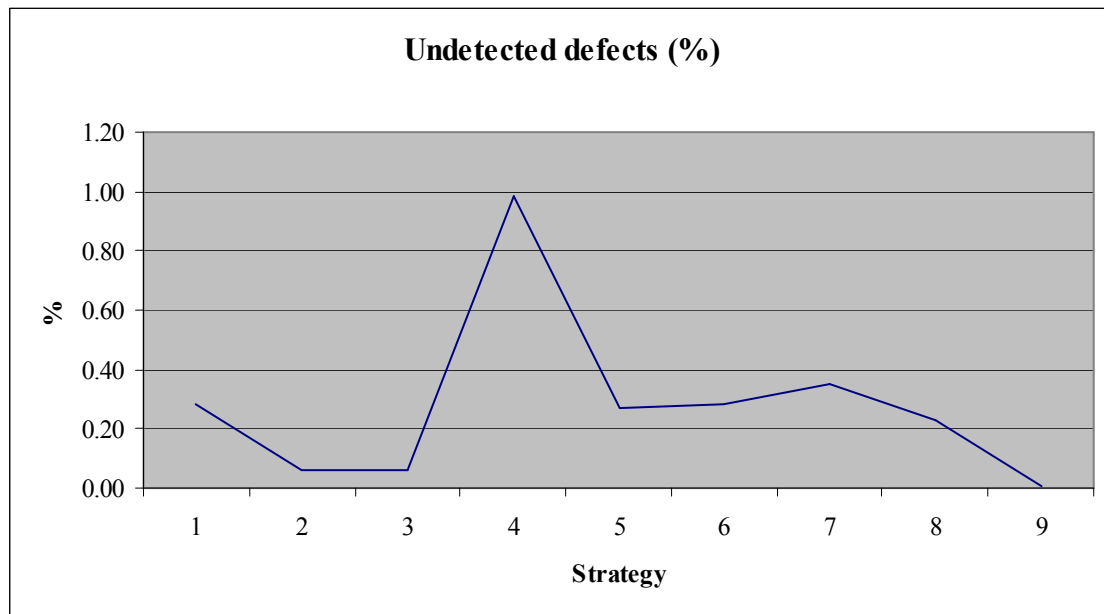


Figure 4.6: Comparison on undetected defects of different inspection strategies

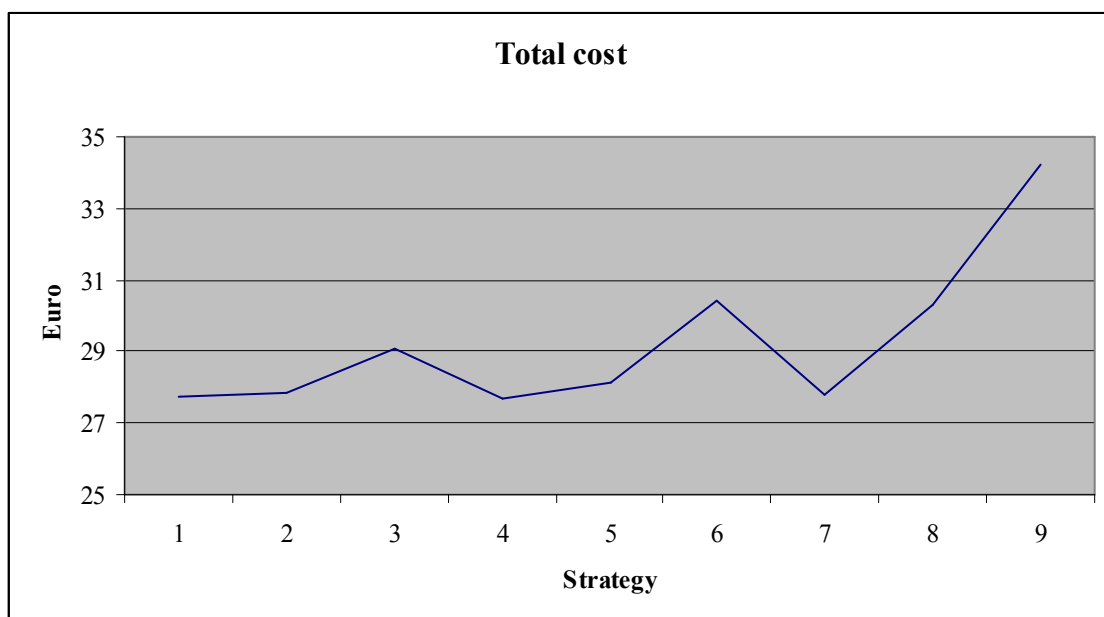


Figure 4.7: Comparison on total cost of different inspection strategies

For the validation, the undetected defects can be compared with the yield calculation. Moreover, the results in the remaining section are collected for the validation purpose. They are compared with the entered conformity rate.

The simulation result of the NZL1 model proves the validation of the model and the result of the simulation aids the company in inspection planning.

4.5.2 Experiment set no. 2: Validation on several components

In this experiment set, the function of simulator for modelling the manufacturing and assemble processes of several components is validated here. The inverter and its components are modelled. The experiment set consists of two experiments which are shown in Table 4.2.

The simulation was run with run length of 3,000,000 hours. The circuit boards arrive into the system in a batch of 1 unit and with the arrival rate of 5,500 minutes. The maximum arrival of the circuit boards is equal to 30,000 batches.

	Automatic insertion and soldering	Hand insertion and soldering	Visual inspection	AOI	ICT	Boundary Scan	Dynamic FKT	Programming	Front assembly	Sys-FKT	ESS	Assembly into power supply	Visual inspection - Power supply	Automatic Sys-FKT - Power supply	Housing assembly	Assembly into controller	Configuration of the inverter	Visual inspection - Inverter	Safety inspection	Automatic Sys-FKT - Inverter	ESS - Inverter	
Experiment 1: use estimated montagefehler (all are considered as a component)	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Experiment 2: "Komponente defekt" failure type is influenced by the components	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 4.2: List of experiments for the inverter modelling

The first experiment was run based on the assumption that all entities in the simulation are considered as a component. In this way, the entity gets the quality characteristic based on the given conformity (Appendix 2). The influence of the component on the finished product is not included. This experiment was done in order to test if the model can give the same result as the company's yield calculation. The yield calculation for inverter and its components in this experiment set is summarized in Appendix 5.

The result from the experiment 1, which is shown in Appendix 6, gives the similar result to the calculated yield. This result will be used to compare with the result from the experiment 2 in order to validate the complete function of the simulator.

The second experiment includes the quality effects of the components on the assembly. The quality of the components influences the quality of the sub-assembly and the assembly through the “Komponente defekt” failure type. The entity does not get the “Komponente defekt” characteristic from the given conformity. Instead, the component’s quality defines the conformity rate for this characteristic, which derived from the influence factor and important factor.

The simulation of this experiment results in a comparable number of defects and costs. However, the experiment 2 shows a slight higher percentage of undetected defects before assembling the housing. This can point out that the conformity of “Komponente defekt” failure type for power supply was a little underestimated in the yield calculation.

4.5.3 Experiment set no. 3: Validation on tolerance planning function

The first two experiment sets have tested the function of the simulator in modelling the production of multi-component product which consists of manufacturing and assembly processes. The experiments also show the use of the simulator in inspection planning.

The tolerance planning is one area that this simulator can assist upon. This ability was proved by this experiment set. It is run on the same run length, arrival rate, and maximum arrival as experiment set no. 2.

Three experiments were done to show how the improvement in component’s quality can affect the quality of the finished product. There are several ways to improve the quality of the component such as process improvement, inspection strategy improvement, etc. The one that applied here is the process improvement which will give the better conformity rate. The experiments differ in the conformity of the component’s quality as shown in Table 4.3.

	Original	Experiment 1	Experiment 2	Experiment 3
Circuit boards Total failure rate (%)	5	3	5	3
Power supply Total failure rate (%)	20	20	15	15

Table 4.3: List of experiments for tolerance planning

The original failure rate from the company was used in the previous experiment set. The conformity rates for each failure type in experiment 1 to experiment 3, which are used as the simulation input data, are converted from the total failure rate in the list of experiment above. The conformity rates for each failure type are presented in detail in Appendix 7.

In this experiment set, the result on total cost and undetected defects are not examined because these performances are influenced by other quality characteristic of the assembly as well. Therefore, it is difficult to evaluate the result from different experiments. Since the quality of the assembly that is affected from the component’s quality can be seen through the “Komponente defekt” failure, this failure was considered in the evaluation instead. The result

in term of this failure type is shown according to the tolerance planning strategy in Figure 4.8 whereas the detail result of experiment set no. 3 is shown in Appendix 8.

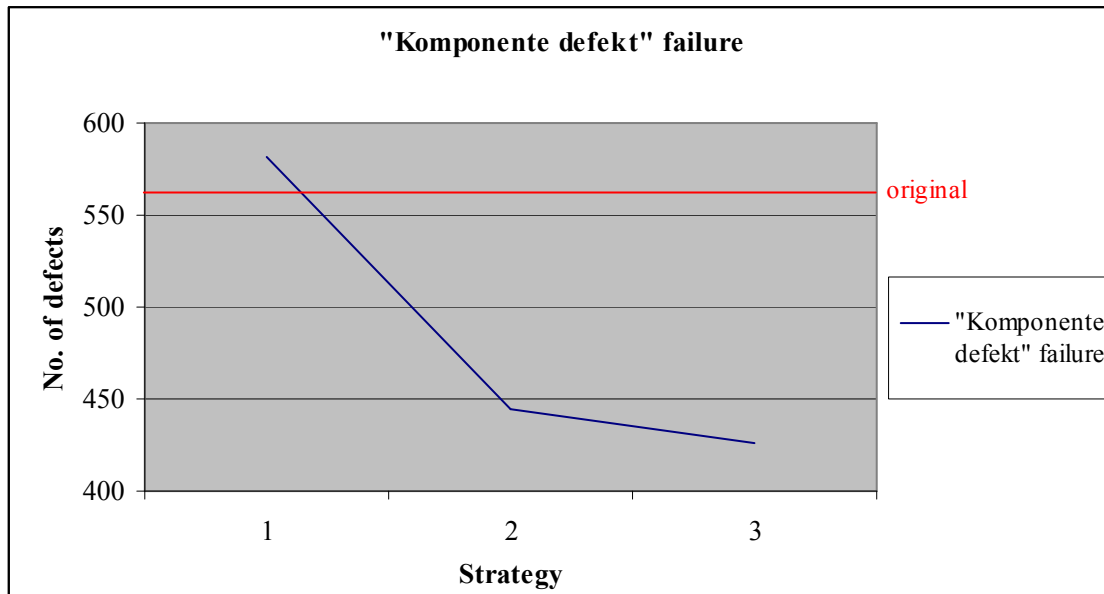


Figure 4.8: Comparison on number of defects of different tolerance planning strategies

The result shows that the process improvement for the manufacturing of circuit board does not make any significant improvement on the quality of the assembly. This is because the improvement of the total failure rate did not differ much from the original level. Moreover, the inspection processes for the circuit board is already quite good therefore the defects are detected before going to the assembly process of the power supply.

On the other hand, the improvement of the power supply assembly process makes a significant improvement on the quality of the assembly. The number of the “Komponente defekt” failure reduces as the total failure rate of the power supply decreases.

From this investigation, the company can know which process they should give attention to. If the company wants to get a better quality of the final product by investing on the process improvement, they should give the priority to the assembly process of the power supply instead of the manufacturing process of the circuit boards. In this way, they will be able to properly plan the tolerances of components and achieve the require quality level of the finished product. They can also make the break-even analysis between the investments that they have to make versus the degree of improvement that they can gain.

5. DISCUSSION AND CONCLUSION

The chapter is dedicated to the discussion on the result and limitations of this research. It also states the room for improvement as a future outlook.

5.1 CRITICAL DISCUSSION

SixSigma simulator was developed to provide the answers to the research questions which are stated in the first chapter of this dissertation. The first question was about the effect of manufactured quality on the assembled quality. Quality of the assembly depends significantly on the quality of the components from manufacturing process. The desired quality level of the assembly could not be reached if the quality of its components is poor.

In order to capture this effect and model the assembled quality based on the components' quality, a mathematical model was developed. The quality of components is translated into a so-called influence factor. A component with a high influence factor is the component with a poor quality. The influence factors of all components are combined into the influence factor of the assembly. The equations for the influence factor were developed based on the concept of classical linear loss function. This mathematical model was integrated into the simulator and was the first feature of the simulator to be validated.

Planning of the inspection and tolerances is not a straight forward task. Several factors must be considered, i.e. quality, costs, and time. There are trade-offs between these factors. To plan the inspection plan or tolerance scheme which favours the quality aspect, one could lose the advantage in terms of costs or time. Thus, the second question was concerning about how the simulator illustrate the performance of each strategy in term of quality, costs, and time.

With SixSigma simulator, the user can investigate how his/her inspection or tolerance plan manipulates the overall performance of the assembly process. The user can enter the desired inspection plan or process capability which reflects the tolerance into the simulator. Arena, which is the based simulation software for this simulator, uses process-interaction method in modelling. This means that the simulator simulates the flow of an object (such as a product) through the system. Therefore, it simulates each and every process to produce a certain product with the entered inspection plan and process capability.

The time that is used in these processes includes processing time, inspecting time, transferring time, and waiting time. They are all collected in the output file. Costs that occurred from all processes are collected. These costs are processing cost, inspection cost, scrap cost, rework cost, raw material cost, transfer cost, waiting cost, holding cost, etc. The quality outcome is also collected in two forms; generated quality and inspected quality. The output can illustrate the quality in each step of the process. Therefore, the user can differentiate the quality of the component from the quality of the assembly.

From these outputs, it is possible to evaluate the performance of different strategies in term of quality, costs, and time. However, the final decision on the suitable inspection or tolerance plan has to be done based on the company's strategy.

Finally, the last question was regarding the assembly process improvement by the simulator based on tolerance planning and inspection planning. The suitable inspection planning and tolerance planning can improve the assembly process in a way that it offers the higher quality of the product, the shorter planning time as well as production time, and the lower total cost. These benefits lead to one important goal in quality management, “customer satisfaction”. Moreover, the assembly process improvement can be achieved as early as in the design and development phase because the inspection and tolerance planning can be evaluated in the simulator without a need of the real system.

Even though the simulation was effectively developed and ready for use, there are still some limitations and room for improvements which will be discussed in the next section.

5.2 LIMITATIONS AND FUTURE OUTLOOK

The development of SixSigma simulator has investigated several aspects. However, there are still some limitations of the simulator and there are also some generated ideas during the research process that have not been explored. Therefore, several future researches are proposed.

First, the research was mainly focusing on the processes that dominate by machines and equipments. The process capability is used extensively as an input data for the simulator. It was not designed for the processes which are significantly manipulated by human. Therefore, human error is not included in this simulator. The further investigation could be done to interpret and embrace the human factor into the simulator.

According to the developed quality effect model, the probability of non-conforming characteristic in assembly process increases linearly as the quality of the component stray away from the tolerance. The existing literatures show that this is not always the case. The modification of the quality effect model which takes Taguchi’s loss function into account could be done as a second proposed research. Afterwards, quality effect model in this SixSigma simulator can be compared with the new quality effect model based on Taguchi’s philosophy.

Each component does not affect equally on the assembly. The weighting factor or important factor was added into the quality effect model. This factor must be taken from the historical data or past learning that the company has on the product. As the SixSigma was implemented in the pilot company, the company already has important factors for each quality characteristic of each component according to their experience. Therefore, the investigation on the important factor was done at a minimum level. It is important to further explore in detail of how to collect and qualify the important factor.

5.3 CONCLUSION

In this study, the simulator was developed in a way that it can assist in improving assembly processes by inspection planning and the corresponding tolerance planning. The mathematical model which can imitate the effect of manufactured quality on the assembled quality was

developed and integrated into the simulator. The function of the simulator can be summarized in the following points:

- Ability to model manufacturing, assembly, inspection, and rework processes
- Ability to simulate both attributive and variable quality characteristics
- Ability to simulate quality characteristic from various distributions
- Dynamic model which change over time depending on failures and maintenance
- Application of weighting for each component
- Ability to combine different quality from different component into one influence that has on the assembly quality
- Output performances are shown in term of quality, cost, and time.
- Allocation of costs and time into several categories such as value added, non-value added, transfer, etc.
- Two sampling schemes: lot-by-lot and continuous
- High flexibility and ease of use
- No programming language required
- Built in Arena simulation software

The simulator was successfully validated with fictional data and also with the actual data from pilot company. The validation proves that the simulator can assist in investigation and evaluation of the tolerance and inspection planning, so that the suitable tolerances and inspection strategy can be selected without the risk of trying it out in the real production environment.

The output from the investigation leads to quality improvement, cost and time reduction. Usually the three aims are contradictory because a higher product quality causes higher costs and requires more time. Thus, the weights for the single goals must be set by each company individually. In this way, the simulator can help to improve the company's goals regardless whether production cost and cycle time are more important than product quality or vice versa. Moreover, the simulator can support the management in justification of investment in inspection equipment or manufacturing processes, for example, by illustrating the consequences of changes in inspection equipment's uncertainty.

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APPENDICES

Appendix 1: Curves for determining values of f and i for a given value of AOQL in Dodge's plan for continuous production CSP-1 /Grant72/.

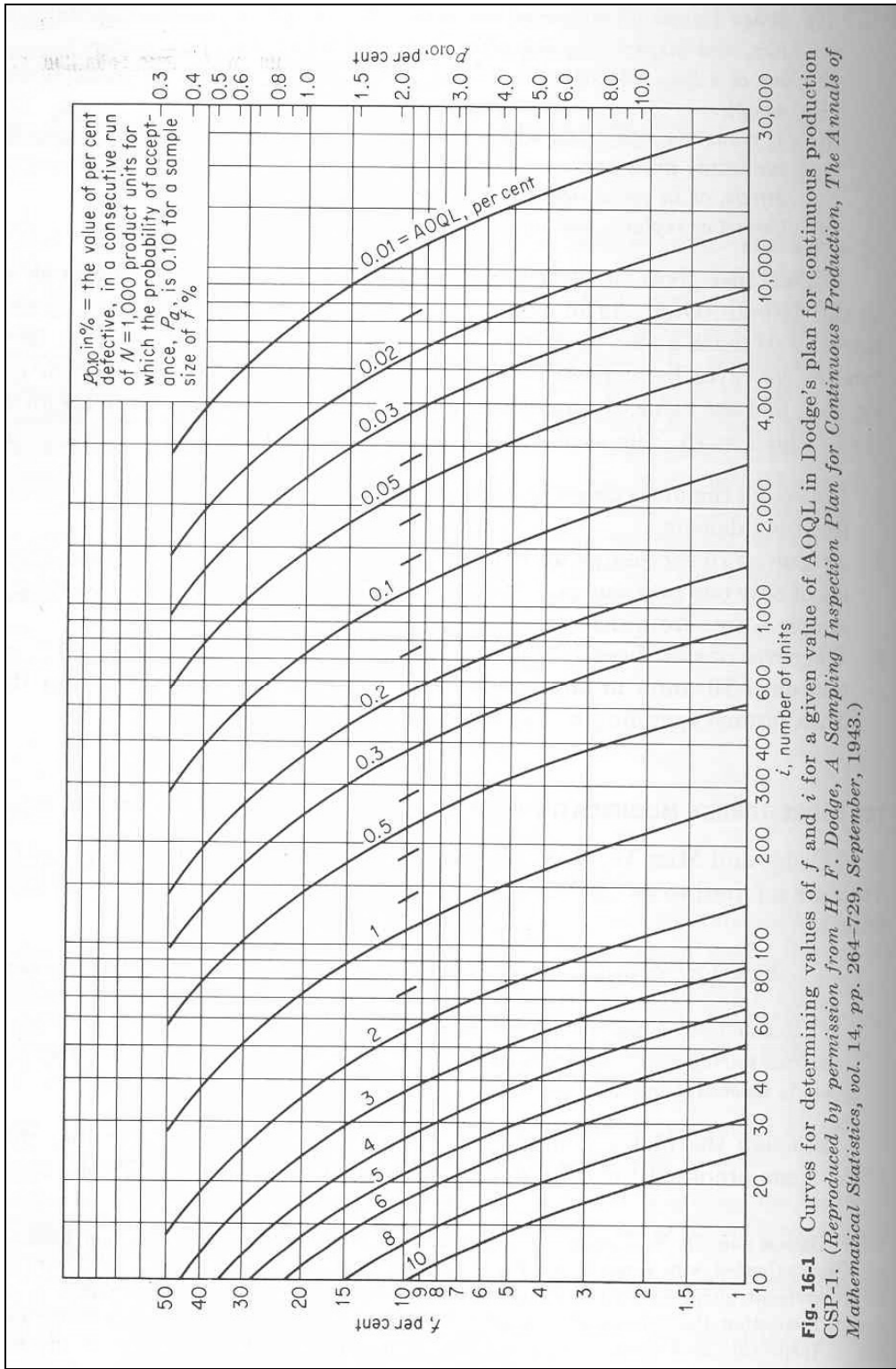


Fig. 16-1 Curves for determining values of f and i for a given value of AOQL in Dodge's plan for continuous production CSP-1. (Reproduced by permission from H. F. Dodge, *A Sampling Inspection Plan for Continuous Production*, *The Annals of Mathematical Statistics*, vol. 14, pp. 264-729, September, 1943.)

Circuit board with front

Failure type	Conformity rate (%)	Failure detection rate (%)							Importance Factor
		Visual inspection	AOI	Boundary Scan	ICT	Dynamic FKT	Sys - FKT	ESS	
Unterlagenfehler	99.90	0.0	0.0	30.0	85.0	60.0	60.0	0.0	1.00
Montagefehler	99.90	0.0	0.0	0.0	0.0	60.0	95.0	85.0	1.00
Leiterplattenfehler mechanisch	99.74	0.0	0.0	30.0	85.0	60.0	60.0	95.0	1.00
Leiterplattenfehler elektrisch	99.74	0.0	0.0	30.0	85.0	60.0	60.0	95.0	1.00
<i>Hand insertion and soldering</i>									
BE fehlt	99.70	5.0	98.0	10.0	98.0	80.0	80.0	0.0	1.00
BE falscher Typ / Wert	99.74	5.0	65.0	5.0	95.0	70.0	70.0	0.0	0.90
BE kein Kontakt	99.64	5.0	65.0	5.0	95.0	70.0	70.0	95.0	0.90
BE Kurzschluss	99.90	20.0	95.0	10.0	98.0	80.0	80.0	0.0	1.00
BE verpolt	99.90	5.0	98.0	5.0	90.0	70.0	70.0	0.0	1.00
BE defekt	99.85	0.0	0.0	5.0	98.0	70.0	70.0	95.0	1.00
<i>Automatic insertion and soldering</i>									
diskrete / passive BE fehlt	99.85	5.0	98.0	10.0	98.0	80.0	80.0	0.0	1.00
diskrete / passive BE falscher Typ / Wert	99.85	5.0	65.0	5.0	95.0	70.0	70.0	0.0	0.90
diskrete / passive BE Position	99.85	5.0	98.0	0.0	0.0	0.0	0.0	0.0	0.05
diskrete / passive BE kein Kontakt	99.74	5.0	95.0	10.0	98.0	80.0	80.0	95.0	1.00
diskrete / passive BE Kurzschluss	99.90	20.0	95.0	10.0	98.0	80.0	80.0	0.0	1.00
diskrete / passive BE verpolt	99.74	5.0	98.0	5.0	90.0	70.0	70.0	0.0	1.00
diskrete / passive BE defekt	99.95	0.0	0.0	5.0	98.0	70.0	70.0	95.0	1.00
IC falscher Typ / Wert	99.59	5.0	65.0	20.0	100.0	100.0	100.0	0.0	1.00
IC verdreht	99.59	5.0	65.0	20.0	100.0	100.0	100.0	0.0	1.00
IC Position	99.90	5.0	98.0	0.0	0.0	0.0	0.0	0.0	0.05
IC kein Kontakt	99.59	5.0	65.0	10.0	90.0	80.0	80.0	95.0	1.00
IC Kurzschluss	99.38	50.0	75.0	10.0	98.0	80.0	80.0	0.0	1.00
IC defekt	99.95	0.0	0.0	30.0	30.0	90.0	80.0	95.0	1.00
andere Fehler	99.99	5.0	0.0	0.0	0.0	20.0	20.0	95.0	0.80

Circuit board without front

Failure type	Conformity	Failure detection rate (%)							Importance
	rate (%)	Visual inspection	AOI	Boundary Scan	ICT	Dynamic FKT	Sys - FKT	ESS	Factor
Unterlagenfehler	99.90	0.0	0.0	30.0	85.0	60.0	60.0	0.0	1.00
Leiterplattenfehler mechanisch	99.74	0.0	0.0	30.0	85.0	60.0	60.0	95.0	1.00
Leiterplattenfehler elektrisch	99.74	0.0	0.0	30.0	85.0	60.0	60.0	95.0	1.00
Hand insertion and soldering									
BE fehlt	99.70	5.0	98.0	10.0	98.0	80.0	80.0	0.0	1.00
BE falscher Typ / Wert	99.74	5.0	65.0	5.0	95.0	70.0	70.0	0.0	0.90
BE kein Kontakt	99.64	5.0	65.0	5.0	95.0	70.0	70.0	95.0	0.90
BE Kurzschluss	99.90	20.0	95.0	10.0	98.0	80.0	80.0	0.0	1.00
BE verpolt	99.90	5.0	98.0	5.0	90.0	70.0	70.0	0.0	1.00
BE defekt	99.85	0.0	0.0	5.0	98.0	70.0	70.0	95.0	1.00
Automatic insertion and soldering									
diskrete / passive BE fehlt	99.85	5.0	98.0	10.0	98.0	80.0	80.0	0.0	1.00
diskrete / passive BE falscher Typ / Wert	99.85	5.0	65.0	5.0	95.0	70.0	70.0	0.0	0.90
diskrete / passive BE Position	99.85	5.0	98.0	0.0	0.0	0.0	0.0	0.0	0.05
diskrete / passive BE kein Kontakt	99.74	5.0	95.0	10.0	98.0	80.0	80.0	95.0	1.00
diskrete / passive BE Kurzschluss	99.90	20.0	95.0	10.0	98.0	80.0	80.0	0.0	1.00
diskrete / passive BE verpolt	99.74	5.0	98.0	5.0	90.0	70.0	70.0	0.0	1.00
diskrete / passive BE defekt	99.95	0.0	0.0	5.0	98.0	70.0	70.0	95.0	1.00
IC falscher Typ / Wert	99.59	5.0	65.0	20.0	100.0	100.0	100.0	0.0	1.00
IC verdreht	99.59	5.0	65.0	20.0	100.0	100.0	100.0	0.0	1.00
IC Position	99.90	5.0	98.0	0.0	0.0	0.0	0.0	0.0	0.05
IC kein Kontakt	99.59	5.0	65.0	10.0	90.0	80.0	80.0	95.0	1.00
IC Kurzschluss	99.38	50.0	75.0	10.0	98.0	80.0	80.0	0.0	1.00
IC defekt	99.95	0.0	0.0	30.0	30.0	90.0	80.0	95.0	1.00
andere Fehler	99.99	5.0	0.0	0.0	0.0	20.0	20.0	95.0	0.80

Power supply

Failure type	Conformity rate (%)	Failure detection rate (%)		Importance Factor
		Visual inspection	Sys - FKT	
Unterlagenfehler	98.88	0.0	90.0	0.95
<i>Production failure</i>				
Montagerfehler	95.09	90.0	90.0	1.00
Gehäuse fehlerhaft	98.88	95.0	0.0	1.00
Kennzeichnungsfehler	97.32	95.0	0.0	1.00
<i>Function failure</i>				
Verdrahtungsfehler	95.54	30.0	95.0	1.00
Sicherheitsrelevante Funktionsfehler	97.77	0.0	90.0	1.00
Komponente defekt	96.65	0.0	95.0	1.00
statische Funktionsfehler	98.88	0.0	90.0	1.00
Echtzeitfehler	99.98	0.0	90.0	1.00
andere Fehler	98.68	30.0	75.0	0.80

Inverter

Failure type	Conformity rate (%)	Failure detection rate (%)				Importance Factor
		Visual inspection	Safety inspection	Sys - FKT	ESS	
Unterlagenfehler	99.55	0.0	0.0	90.0	0.0	1.00
<i>Safety failure</i>						
Übergangswiderstandsfehler	98.88	0.0	100.0	0.0	0.0	1.00
Isolationsfehler	98.88	0.0	100.0	0.0	0.0	1.00
Grenztemperaturfehler	98.88	0.0	100.0	0.0	0.0	1.00
<i>Production failure</i>						
Montagefehler	96.43	90.0	0.0	90.0	90.0	1.00
Gehäuse fehlerhaft	98.88	95.0	0.0	0.0	0.0	1.00
Kennzeichnungsfehler	97.77	95.0	0.0	0.0	0.0	1.00
<i>Function failure</i>						
Verdrahtungsfehler	96.43	85.0	0.0	90.0	0.0	1.00
Schnittstellenfehler BUS und Digital	95.98	25.0	0.0	98.0	90.0	1.00
Sicherheitsrelevante Funktionsfehler	98.66	0.0	0.0	95.0	90.0	1.00
Komponente defekt	98.46	0.0	0.0	95.0	99.0	1.00
statische Funktionsfehler	99.55	0.0	0.0	90.0	99.0	1.00
Echtzeitfehler	99.98	0.0	0.0	90.0	90.0	1.00
andere Fehler	99.33	10.0	0.0	50.0	80.0	0.80

Appendix 3: Simulation result of experiment set 1

Strategy	1	2	3	4	5	6	7	8	9
Incoming parts	30000	30000	30000	30000	30000	30000	30000	30000	30000
Outgoing parts (finished parts)	29700	29700	29600	29700	29700	29500	29700	29600	29300
Undetected defects (Schlupf)	85	19	17	292	81	84	104	67	1
Undetected defects (%)	0.29	0.06	0.06	0.98	0.27	0.28	0.35	0.23	0.00
Avg. value-added cost	22.39	22.48	22.56	22.36	22.72	22.72	22.46	22.49	22.82
Avg. non value-added cost	5.34	5.37	6.51	5.33	5.39	7.68	5.34	7.82	11.41
Defects (units)									
Unterlagenfehler	23	25	20	31	28	25	29	30	30
Montagefehler	28	23	24	33	32	31	32	35	25
Leiterplattenfehler mechanisch	76	77	92	64	83	76	71	61	102
Leiterplattenfehler elektrisch	89	84	74	84	91	65	82	87	68
BE fehlt	93	106	81	98	85	108	82	88	76
BE falsch Typ/Wert	88	89	69	80	80	90	82	81	91
BE kein Kontakt	119	114	95	121	118	116	115	118	100
BE Kurzschluss	33	27	36	27	29	28	38	30	29
BE verpolt	25	39	24	36	36	24	33	28	30
BE defekt	58	45	41	51	40	47	45	44	47
diskrete/passive BE fehlt	58	55	37	49	54	41	49	49	55
diskrete/passive BE falscher Typ/Wert	38	50	42	47	49	39	34	41	49
diskrete/passive BE Position	37	34	42	40	39	53	51	33	50
diskrete/passive BE kein Kontakt	86	74	68	86	78	67	78	96	79
diskrete/passive BE Kurzschluss	32	30	26	33	27	29	33	36	21
diskrete/passive BE verpolt	81	71	92	78	79	76	80	80	69
diskrete/passive BE defekt	18	13	16	15	11	13	17	12	12
IC falscher Typ/Wert	114	122	119	123	106	104	120	126	120
IC verdreht	118	148	137	121	113	114	129	135	140
IC Position	26	26	40	32	17	31	26	22	30
IC kein Kontakt	124	106	124	107	111	123	111	120	120
IC Kurzschluss	202	181	149	194	193	202	196	183	171
IC defekt	7	17	17	11	10	14	20	14	23
andere Fehler	3	3	6	3	3	3	3	4	4
Total	1576	1559	1471	1564	1512	1519	1556	1553	1541
No. of units that enter processes									
Automatic insertion and soldering	30000	30000	30000	30000	30000	30000	30000	30000	30000
Hand insertion and soldering	30000	30000	30000	30000	30000	30000	30000	30000	30000
Visual inspection	30000	-	30000	30000	30000	30000	30000	30000	30000
AOI	-	30000	29900	-	-	-	-	-	29900
ICT	29900	29900	29800	-	-	29900	29900	29900	29800
Boundary Scan	-	-	-	29900	-	29800	-	-	29700
Dynamic FKT	-	-	-	-	29900	29700	-	-	29600
Programming	29800	29800	29700	29800	29800	29600	29800	29800	29500
Front assembly	29800	29800	29700	29800	29800	29600	29800	29800	29500
Sys-FKT	29800	29800	29700	29800	29800	29600	-	29800	29500
ESS	-	-	-	-	-	-	29800	29700	29400
No. of units that exit the system									
	29700	29700	29600	29700	29700	29500	29700	29600	29300

NZL1 Controllercard Art.: 22529

Fehlerrate BG in %	5.0		Sichtprüfung		AOI		Boundary Scan		ICT		dynamischer FKT		Sys - FKT		ESS		Bedeutung	
Gesamtfehler	0.0513																	
Fehlerarten	in %	FPB	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf
Unterlagenfehler	2.0	0.0010	0.0	0.0010	0.0	0.0010	30.0	0.0007	85.0	0.0001	60.0	0.0000	60.0	0.00002	0.0	0.00002	100	0.000017
Montagefehler	2.0	0.0010	0.0	0.0010	0.0	0.0010	0.0	0.0010	0.0	0.0010	60.0	0.0004	95.0	0.00002	85.0	0.00000	100	0.000003
Leiterplattenfehler mechanisch	5.0	0.0026	0.0	0.0026	0.0	0.0026	30.0	0.0018	85.0	0.0003	60.0	0.0001	60.0	0.00004	95.0	0.00000	100	0.000002
Leiterplattenfehler elektrisch	5.0	0.0026	0.0	0.0026	0.0	0.0026	30.0	0.0018	85.0	0.0003	60.0	0.0001	60.0	0.00004	95.0	0.00000	100	0.000002
Bedrahtete Bestückung																		
BE fehlt	5.9	0.0030	5.0	0.0029	98.0	0.0001	10.0	0.0001	98.0	0.0000	80.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
BE falscher Typ / Wert	5.0	0.0026	5.0	0.0024	65.0	0.0009	5.0	0.0008	95.0	0.0000	70.0	0.0000	70.0	0.00000	0.0	0.00000	90	0.000003
BE kein Kontakt	7.0	0.0036	5.0	0.0034	65.0	0.0012	5.0	0.0011	95.0	0.0001	70.0	0.0000	70.0	0.00001	95.0	0.00000	90	0.000000
BE Kurzschluss	2.0	0.0010	20.0	0.0008	95.0	0.0000	10.0	0.0000	98.0	0.0000	80.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
BE verpolt	2.0	0.0010	5.0	0.0010	98.0	0.0000	5.0	0.0000	90.0	0.0000	70.0	0.0000	70.0	0.00000	0.0	0.00000	100	0.000000
BE defekt	3.0	0.0015	0.0	0.0015	0.0	0.0015	5.0	0.0015	98.0	0.0000	70.0	0.0000	70.0	0.00000	95.0	0.00000	100	0.000000
SMD Bestückung																		
diskrete / passive BE fehlt	3.0	0.0015	5.0	0.0015	98.0	0.0000	10.0	0.0000	98.0	0.0000	80.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE falscher Typ / Wert	3.0	0.0015	5.0	0.0015	65.0	0.0005	5.0	0.0005	95.0	0.0000	70.0	0.0000	70.0	0.00000	0.0	0.00000	90	0.000002
diskrete / passive BE Position	3.0	0.0015	5.0	0.0015	98.0	0.0000	0.0	0.0000	0.0	0.0000	0.0	0.0000	0.0	0.00003	0.0	0.00003	5	0.000001
diskrete / passive BE kein Kontakt	5.0	0.0026	5.0	0.0024	95.0	0.0001	10.0	0.0001	98.0	0.0000	80.0	0.0000	80.0	0.00000	95.0	0.00000	100	0.000000
diskrete / passive BE Kurzschluss	2.0	0.0010	20.0	0.0008	95.0	0.0000	10.0	0.0000	98.0	0.0000	80.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE verpolt	5.0	0.0026	5.0	0.0024	98.0	0.0000	5.0	0.0000	90.0	0.0000	70.0	0.0000	70.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE defekt	1.0	0.0005	0.0	0.0005	0.0	0.0005	5.0	0.0005	98.0	0.0000	70.0	0.0000	70.0	0.00000	95.0	0.00000	100	0.000000
IC falscher Typ / Wert	8.0	0.0041	5.0	0.0039	65.0	0.0014	20.0	0.0011	100.0	0.0000	100.0	0.0000	100.0	0.00000	0.0	0.00000	100	0.000000
IC verdreht	8.0	0.0041	5.0	0.0039	65.0	0.0014	20.0	0.0011	100.0	0.0000	100.0	0.0000	100.0	0.00000	0.0	0.00000	100	0.000000
IC Position	2.0	0.0010	5.0	0.0010	98.0	0.0000	0.0	0.0000	0.0	0.0000	0.0	0.0000	0.0	0.00002	0.0	0.00002	5	0.000001
IC kein Kontakt	8.0	0.0041	5.0	0.0039	65.0	0.0014	10.0	0.0012	90.0	0.0001	80.0	0.0000	80.0	0.00000	95.0	0.00000	100	0.000000
IC Kurzschluss	12.0	0.0062	50.0	0.0031	75.0	0.0008	10.0	0.0007	98.0	0.0000	80.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000001
IC defekt	1.0	0.0005	0.0	0.0005	0.0	0.0005	30.0	0.0004	30.0	0.0003	90.0	0.0000	80.0	0.00001	95.0	0.00000	100	0.000000
andere Fehler	0.1	0.0001	5.0	0.0000	0.0	0.0000	0.0	0.0000	0.0	0.0000	20.0	0.0000	20.0	0.00003	95.0	0.00000	80	0.000001
Gesamtfehler	100.0	0.0513		0.0461		0.0176		0.0146		0.0023		0.0009		0.00023		0.00008		0.000036

Circuit board with front

Fehlerrate BG in %	5.0		Sichtprüfung		AOI		ICT		Sys - FKT		ESS		Bedeutung	
Gesamtfehler	0.0513													
Fehlerarten	in %	FPB	in %	Schlupf	in %	Schlupf	Fehlerabdeckung		in %	Schlupf	in %	Schlupf	in %	Schlupf bewertet
Unterlagenfehler	2.0	0.0010	0.0	0.0010	0.0	0.0010	85.0	0.0002	60.0	0.00006	0.0	0.00006	100	0.000062
Montagefehler	2.0	0.0010	0.0	0.0010	0.0	0.0010	0.0	0.0010	95.0	0.00005	85.0	0.00001	100	0.000008
Leiterplattenfehler mechanisch	5.0	0.0026	0.0	0.0026	0.0	0.0026	85.0	0.0004	60.0	0.00015	95.0	0.00001	100	0.000008
Leiterplattenfehler elektrisch	5.0	0.0026	0.0	0.0026	0.0	0.0026	85.0	0.0004	60.0	0.00015	95.0	0.00001	100	0.000008
Bedrahtete Bestückung														
BE fehlt	5.9	0.0030	5.0	0.0029	98.0	0.0001	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
BE falscher Typ / Wert	5.0	0.0026	5.0	0.0024	65.0	0.0009	95.0	0.0000	70.0	0.00001	0.0	0.00001	90	0.000012
BE kein Kontakt	7.0	0.0036	5.0	0.0034	65.0	0.0012	95.0	0.0001	70.0	0.00002	95.0	0.00000	90	0.000001
BE Kurzschluss	2.0	0.0010	20.0	0.0008	95.0	0.0000	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
BE verpolt	2.0	0.0010	5.0	0.0010	98.0	0.0000	90.0	0.0000	70.0	0.00000	0.0	0.00000	100	0.000001
BE defekt	3.0	0.0015	0.0	0.0015	0.0	0.0015	98.0	0.0000	70.0	0.00001	95.0	0.00000	100	0.000000
SMD Bestückung														
diskrete / passive BE fehlt	3.0	0.0015	5.0	0.0015	98.0	0.0000	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE falscher Typ / Wert	3.0	0.0015	5.0	0.0015	65.0	0.0005	95.0	0.0000	70.0	0.00001	0.0	0.00001	90	0.000007
diskrete / passive BE Position	3.0	0.0015	5.0	0.0015	98.0	0.0000	0.0	0.0000	0.0	0.00003	0.0	0.00003	5	0.000001
diskrete / passive BE kein Kontakt	5.0	0.0026	5.0	0.0024	95.0	0.0001	98.0	0.0000	80.0	0.00000	95.0	0.00000	100	0.000000
diskrete / passive BE Kurzschluss	2.0	0.0010	20.0	0.0008	95.0	0.0000	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE verpolt	5.0	0.0026	5.0	0.0024	98.0	0.0000	90.0	0.0000	70.0	0.00000	0.0	0.00000	100	0.000001
diskrete / passive BE defekt	1.0	0.0005	0.0	0.0005	0.0	0.0005	98.0	0.0000	70.0	0.00000	95.0	0.00000	100	0.000000
IC falscher Typ / Wert	8.0	0.0041	5.0	0.0039	65.0	0.0014	100.0	0.0000	100.0	0.00000	0.0	0.00000	100	0.000000
IC verdreht	8.0	0.0041	5.0	0.0039	65.0	0.0014	100.0	0.0000	100.0	0.00000	0.0	0.00000	100	0.000000
IC Position	2.0	0.0010	5.0	0.0010	98.0	0.0000	0.0	0.0000	0.0	0.00002	0.0	0.00002	5	0.000001
IC kein Kontakt	8.0	0.0041	5.0	0.0039	65.0	0.0014	90.0	0.0001	80.0	0.00003	95.0	0.00000	100	0.000001
IC Kurzschluss	12.0	0.0062	50.0	0.0031	75.0	0.0008	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000003
IC defekt	1.0	0.0005	0.0	0.0005	0.0	0.0005	30.0	0.0004	80.0	0.00007	95.0	0.00000	100	0.000004
andere Fehler	0.1	0.0001	5.0	0.0000	0.0	0.0000	0.0	0.0000	20.0	0.00004	95.0	0.00000	80	0.000002
Gesamtfehler	100.0	0.0513		0.0461		0.0176		0.0027		0.00066		0.00017		0.000119

Circuit board without front

Fehlerrate BG in % Gesamtfehler	5.0		Sichtprüfung		AOI		ICT		Sys - FKT		ESS		Bedeutung	
	in %	FPB	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf
Fehlerarten	Fehlerabdeckung													
	in %	FPB	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf
Unterlagenfehler	2.0	0.0010	0.0	0.0010	0.0	0.0010	85.0	0.0002	60.0	0.00006	0.0	0.00006	100	0.000062
Leiterplattenfehler mechanisch	5.0	0.0026	0.0	0.0026	0.0	0.0026	85.0	0.0004	60.0	0.00015	95.0	0.00001	100	0.000008
Leiterplattenfehler elektrisch	5.0	0.0026	0.0	0.0026	0.0	0.0026	85.0	0.0004	60.0	0.00015	95.0	0.00001	100	0.000008
Bedrahtete Bestückung														
BE fehlt	5.9	0.0030	5.0	0.0029	98.0	0.0001	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
BE falscher Typ / Wert	5.0	0.0026	5.0	0.0024	65.0	0.0009	95.0	0.0000	70.0	0.00001	0.0	0.00001	90	0.000012
BE kein Kontakt	7.0	0.0036	5.0	0.0034	65.0	0.0012	95.0	0.0001	70.0	0.00002	95.0	0.00000	90	0.000001
BE Kurzschluss	2.0	0.0010	20.0	0.0008	95.0	0.0000	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
BE verpolt	2.0	0.0010	5.0	0.0010	98.0	0.0000	90.0	0.0000	70.0	0.00000	0.0	0.00000	100	0.000001
BE defekt	3.0	0.0015	0.0	0.0015	0.0	0.0015	98.0	0.0000	70.0	0.00001	95.0	0.00000	100	0.000000
SMD Bestückung														
diskrete / passive BE fehlt	3.0	0.0015	5.0	0.0015	98.0	0.0000	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE falscher Typ / Wert	3.0	0.0015	5.0	0.0015	65.0	0.0005	95.0	0.0000	70.0	0.00001	0.0	0.00001	90	0.000007
diskrete / passive BE Position	3.0	0.0015	5.0	0.0015	98.0	0.0000	0.0	0.0000	0.0	0.00003	0.0	0.00003	5	0.000001
diskrete / passive BE kein Kontakt	5.0	0.0026	5.0	0.0024	95.0	0.0001	98.0	0.0000	80.0	0.00000	95.0	0.00000	100	0.000000
diskrete / passive BE Kurzschluss	2.0	0.0010	20.0	0.0008	95.0	0.0000	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000000
diskrete / passive BE verpolt	5.0	0.0026	5.0	0.0024	98.0	0.0000	90.0	0.0000	70.0	0.00000	0.0	0.00000	100	0.000001
diskrete / passive BE defekt	1.0	0.0005	0.0	0.0005	0.0	0.0005	98.0	0.0000	70.0	0.00000	95.0	0.00000	100	0.000000
IC falscher Typ / Wert	8.0	0.0041	5.0	0.0039	65.0	0.0014	100.0	0.0000	100.0	0.00000	0.0	0.00000	100	0.000000
IC verdreht	8.0	0.0041	5.0	0.0039	65.0	0.0014	100.0	0.0000	100.0	0.00000	0.0	0.00000	100	0.000000
IC Position	2.0	0.0010	5.0	0.0010	98.0	0.0000	0.0	0.0000	0.0	0.00002	0.0	0.00002	5	0.000001
IC kein Kontakt	8.0	0.0041	5.0	0.0039	65.0	0.0014	90.0	0.0001	80.0	0.00003	95.0	0.00000	100	0.000001
IC Kurzschluss	12.0	0.0062	50.0	0.0031	75.0	0.0008	98.0	0.0000	80.0	0.00000	0.0	0.00000	100	0.000003
IC defekt	1.0	0.0005	0.0	0.0005	0.0	0.0005	30.0	0.0004	80.0	0.00007	95.0	0.00000	100	0.000004
andere Fehler	2.1	0.0011	5.0	0.0010	0.0	0.0010	0.0	0.0010	20.0	0.00082	95.0	0.00004	80	0.000033
Gesamtfehler	100.0	0.0513		0.0461		0.0176		0.0027		0.00139		0.00020		0.000143

Power supply

Fehlerrate BG in %	20.0		Sichtprüfung		Automatischer Sys - FKT		Bedeutung	
Gesamtfehler		0.2231						
Fehlerarten	in %	FPB	in %	Fehlerabdeckung Schlupf	in %	Schlupf	in %	Schlupf bewertet
Unterlagenfehler	5.0	0.0112	0.0	0.0112	90.0	0.0011	95	0.001060
Produktionsfehler								
Montagefehler	22.0	0.0491	90.0	0.0049	90.0	0.0005	100	0.000491
Gehäuse fehlerhaft	5.0	0.0112	95.0	0.0006	0.0	0.0006	100	0.000558
Kennzeichnungsfehler	12.0	0.0268	95.0	0.0013	0.0	0.0013	100	0.001339
Funktionsfehler								
Verdrahtungsfehler	20.0	0.0446	30.0	0.0312	95.0	0.0016	100	0.001562
Sicherheitsrelevante Funktionsfehler	10.0	0.0223	0.0	0.0223	90.0	0.0022	100	0.002231
Komponente defekt	15.0	0.0335	0.0	0.0335	95.0	0.0017	100	0.001674
statische Funktionsfehler	5.0	0.0112	0.0	0.0112	90.0	0.0011	100	0.001116
Echtzeitfehler	0.1	0.0002	0.0	0.0002	90.0	0.0000	100	0.000022
andere Fehler	5.9	0.0132	30.0	0.0092	75.0	0.0023	80	0.003405
Gesamtfehler	100.0	0.2231		0.1256		0.0124		0.013458

Inverter

Fehlerrate BG in %	20.0		Sichtprüfung		Sicherheitsprüfung		Automatischer Sys - FKT		ESS		Bedeutung	
	0.2231											
Fehlerarten	in %	FPB	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf	in %	Schlupf bewertet
Unteralagenfehler	2.0	0.0045	0.0	0.0045	0.0	0.0045	90.0	0.0004	0.0	0.0004	100	0.001116
Sicherheitsfehler												
Übergangswiderstandsfehler	5.0	0.0112	0.0	0.0112	100.0	0.0000	0.0	0.0000	0.0	0.0000	100	0.000000
Isolationsfehler	5.0	0.0112	0.0	0.0112	100.0	0.0000	0.0	0.0000	0.0	0.0000	100	0.000000
Grenztemperaturfehler	5.0	0.0112	0.0	0.0112	100.0	0.0000	0.0	0.0000	0.0	0.0000	100	0.000000
Produktionsfehler												
Montagefehler	16.0	0.0357	90.0	0.0036	0.0	0.0036	90.0	0.0004	90.0	0.0000	100	0.000036
Gehäuse fehlerhaft	5.0	0.0112	95.0	0.0006	0.0	0.0006	0.0	0.0006	0.0	0.0006	100	0.000558
Kennzeichnungsfehler	10.0	0.0223	95.0	0.0011	0.0	0.0011	0.0	0.0011	0.0	0.0011	100	0.001116
Funktionsfehler												
Verdrahtungsfehler	16.0	0.0357	85.0	0.0054	0.0	0.0054	90.0	0.0005	0.0	0.0005	100	0.000536
Schnittstellenfehler BUS und Digital	18.0	0.0402	25.0	0.0301	0.0	0.0301	98.0	0.0006	90.0	0.0001	100	0.000060
Sicherheitsrelevante Funktionsfehler	6.0	0.0134	0.0	0.0134	0.0	0.0134	95.0	0.0007	90.0	0.0001	100	0.000067
Komponente defekt	6.9	0.0154	0.0	0.0154	0.0	0.0154	95.0	0.0008	99.0	0.0000	100	0.000008
statische Funktionsfehler	2.0	0.0045	0.0	0.0045	0.0	0.0045	90.0	0.0004	99.0	0.0000	100	0.000004
Echtzeitfehler	0.1	0.0002	0.0	0.0002	0.0	0.0002	90.0	0.0000	90.0	0.0000	100	0.000002
andere Fehler	3.0	0.0067	10.0	0.0060	0.0	0.0060	50.0	0.0030	80.0	0.0006	80	0.000803
Gesamtfehler	100.0	0.2231		0.1182		0.0847		0.0085		0.0034		0.004306

Appendix 6: Simulation result of experiment set no. 2

	Experiment 1	Experiment 2	
Incoming & outgoing parts			units
NZL1 (entity # 1)	30000	30000	
NMF1 (entity # 2)	30000	30000	
NAS2 (entity # 3)	30000	30000	
NSG2 (entity # 4)	30000	30000	
UGP1 (entity # 5)	30000	30000	
Leistungsteil (entity # 7)	30000	30000	
Leistungsteil + Steckbox (entity # 8)	30000	30000	
IZL1 (entity # 10)	30000	30000	
ILT1 (entity # 11)	30000	30000	
ISG1 (entity # 12)	30000	30000	
Steckbox (entity # 13)	30000	30000	
Finished product (Steuerung_entity # 9)	30000	30000	units
Undetected defects at LTT (Schlupf)	16	12	units
Undetected defects at LTT (Schlupf in %)	0.05	0.04	%
Undetected defects at SB (Schlupf)	342	276	
Undetected defects at SB (Schlupf in %)	1.14	0.92	%
Undetected defects at FP (Schlupf)	25	295	
Undetected defects at FP (Schlupf in %)	0.08	0.98	%
Undetected defects to customers (Schlupf)	97	87	
Undetected defects to customers (Schlupf in %)	0.32	0.29	
Avg. value-added cost	230.01	230.09	€
Avg. non value-added cost	510.06	510.02	€
Total cost	740.07	740.11	€
Avg. flowtime IZL1 (entity #10)	12.25	12.264	hour
Avg. flowtime ILT1 (entity #11)	12.25	12.264	hour
Avg. flowtime ISG1 (entity #12)	12.25	12.264	hour
Avg. flowtime_Leistungsteil	1.6143	1.6021	hour
Total avg. flowtime for Leistungsteil	13.8643	13.8661	hour
Avg. flowtime_Steckbox (entity 13)	12.697	12.699	hour
Avg. flowtime_Leistungsteil + Steckbox	1.3169	1.317	hour
Total avg. flowtime for Leistungsteil + Steckb	15.1812	15.1831	hour
Avg. flowtime NZL1 (entity 1)	15.181	15.183	hour
Avg. flowtime NMF1 (entity 2)	15.181	15.183	hour
Avg. flowtime NAS2 (entity 3)	15.181	15.183	hour
Avg. flowtime NSG2 (entity 4)	15.181	15.183	hour
Avg. flowtime UGP1 (entity 5)	15.181	15.183	hour
Avg. flowtime_Steuerung	1.3867	1.3877	hour
Total avg. flowtime for finished product	16.5679	16.5708	hour

	Experiment 1	Experiment 2	
Defects			
Leiterplattenfehler mechanisch	663	648	units
Leiterplattenfehler elektrisch	603	651	units
BE fehlt	732	691	units
BE falsch Typ/Wert	610	647	units
BE kein Kontakt	901	862	units
BE Kurzschluss	239	200	units
BE verpolt	248	221	units
BE defekt	350	338	units
diskrete / passive BE fehlt	351	390	units
diskrete / passive BE falscher Typ/Wert	381	360	units
diskrete / passive BE Position	357	379	units
diskrete / passive BE kein Kontakt	621	619	units
diskrete / passive BE Kurzschluss	273	240	units
diskrete / passive BE verpolt	639	571	units
diskrete / passive BE defekt	133	113	units
IC falscher Typ/Wert	957	1016	units
IC verdreht	976	944	units
IC Position	258	254	units
IC kein Kontakt	985	937	units
IC Kurzschluss	1405	1517	units
IC defekt	120	127	units
Übergangswiderstandsfehler	345	360	units
Isolationsfehler	303	334	units
Grenztemperaturfehler	339	350	units
Schnittstellenfehler BUS und Digital/Analog EA	1188	1184	
Unterlagenfehler	660	720	units
Montagefehler	2722	2713	units
Gehäuse fehlerhaft	695	696	units
Kennzeichnungs fehler	1476	1450	units
Verdrahtungsfehler	2439	2377	units
Sicherheitsrelevante Funktionsfehler	1059	1067	units
Komponente defekt	1459	556	units
statische Funktionsfehler	453	465	units
Echtzeitfehler	15	7	units
andere Fehler	636	635	units
Total	25591	24639	units

	Experiment 1	Experiment 2	
Processes			
<i>IN</i>			units
SMD Bestückung und Löten	240000	240000	
Bedrahtete Bestückung und Löten	240000	240000	
Sichtprüfung	240000	240000	
Rework Sichtprüfung	1157	1210	
AOI	240000	240000	
Rework AOI	6760	6658	
ICT	240000	240000	
Rework ICT	3481	3463	
Boundary Scan	0	0	
Rework Boundary Scan	0	0	
Dynamischer FKT	0	0	
Rework Dynamischer FKT	0	0	
Programmierung	240000	240000	
Montage (Frontplatte)	180000	180000	
Sys-FKT	240000	240000	
Rework Sys-FKT	454	435	
ESS	240000	240000	
Rework ESS	174	180	
Aufbau mit Leistungsteil	30000	30000	
Sichtprüfung - Leistungsteil	30000	30000	
Rework Sichtprüfung - Leistungsteil	2807	2893	
Automatischer Sys-FKT_Leistungsteil	30000	30000	
Rework Automatischer Sys-FKT_Leistungsteil	3162	2226	
Steckboxeinbau	30000	30000	
Bestückung der Steckbox	30000	30000	
Konfiguration der Steckbox	30000	30000	
Sichtprüfung - Steuerung	30000	30000	
Rework Sichtprüfung - Steuerung	2990	3010	
Sicherheitsprüfung	30000	30000	
Rework Sicherheitsprüfung	977	1038	
Automatischer Sys-FKT_Steuerung	30000	30000	
Rework Automatischer Sys-FKT_Steuerung	2086	1938	
ESS - Steuerung	30000	30000	
Rework ESS - Steuerung	121	130	
<i>OUT</i>			units
System out	30000	30000	

Appendix 7: Conformity rates in percentage for experiment set no. 3

	circuit board with front			circuit board without front		
	3.0	0.0305	Conformity rate	3.0	0.0305	Conformity rate
Fehlerrate BG in %	3.0			3.0		
Gesamtfehler		0.0305			0.0305	
Fehlerarten	in %	FPB	Conformity rate	in %	FPB	Conformity rate
Unterlagenfehler	2.0	0.0006	99.94%	2.0	0.0006	99.94%
Montagefehler	2.0	0.0006	99.94%			
Leiterplattenfehler mechanisch	5.0	0.0015	99.85%	5.0	0.0015	99.85%
Leiterplattenfehler elektrisch	5.0	0.0015	99.85%	5.0	0.0015	99.85%
Bedrahtete Bestückung						
BE fehlt	5.9	0.0018	99.82%	5.9	0.0018	99.82%
BE falscher Typ / Wert	5.0	0.0015	99.85%	5.0	0.0015	99.85%
BE kein Kontakt	7.0	0.0021	99.79%	7.0	0.0021	99.79%
BE Kurzschluss	2.0	0.0006	99.94%	2.0	0.0006	99.94%
BE verpolt	2.0	0.0006	99.94%	2.0	0.0006	99.94%
BE defekt	3.0	0.0009	99.91%	3.0	0.0009	99.91%
SMD Bestückung						
diskrete / passive BE fehlt	3.0	0.0009	99.91%	3.0	0.0009	99.91%
diskrete / passive BE falscher Typ / Wert	3.0	0.0009	99.91%	3.0	0.0009	99.91%
diskrete / passive BE Position	3.0	0.0009	99.91%	3.0	0.0009	99.91%
diskrete / passive BE kein Kontakt	5.0	0.0015	99.85%	5.0	0.0015	99.85%
diskrete / passive BE Kurzschluss	2.0	0.0006	99.94%	2.0	0.0006	99.94%
diskrete / passive BE verpolt	5.0	0.0015	99.85%	5.0	0.0015	99.85%
diskrete / passive BE defekt	1.0	0.0003	99.97%	1.0	0.0003	99.97%
IC falscher Typ / Wert	8.0	0.0024	99.76%	8.0	0.0024	99.76%
IC verdreht	8.0	0.0024	99.76%	8.0	0.0024	99.76%
IC Position	2.0	0.0006	99.94%	2.0	0.0006	99.94%
IC kein Kontakt	8.0	0.0024	99.76%	8.0	0.0024	99.76%
IC Kurzschluss	12.0	0.0037	99.63%	12.0	0.0037	99.63%
IC defekt	1.0	0.0003	99.97%	1.0	0.0003	99.97%
andere Fehler	0.1	0.0000	100.00%	2.1	0.0006	99.94%
Gesamtfehler	100.0	0.0305	96.95%	100.0	0.0305	96.95%

Power supply			
Fehlerrate BG in %	15.0		
Gesamtfehler		0.1625	
Fehlerarten	in %	FPB	Conformity rate
Unterlagenfehler	5.0	0.0081	99.19%
Produktionsfehler			
Montagefehler	22.0	0.0358	96.42%
Gehäuse fehlerhaft	5.0	0.0081	99.19%
Kennzeichnungsfehler	12.0	0.0195	98.05%
Funktionsfehler			
Verdrahtungsfehler	20.0	0.0325	96.75%
Sicherheitsrelevante Funktionsfehler	10.0	0.0163	98.37%
Komponente defekt	15.0	0.0244	97.56%
statische Funktionsfehler	5.0	0.0081	99.19%
Echtzeitfehler	0.1	0.0002	99.98%
andere Fehler	5.9	0.0096	99.04%
Gesamtfehler	100.0	0.1625	83.75%

Appendix 8: Simulation result of experiment set no. 3

	Experiment 1	Experiment 2	Experiment 3	
Incoming & outgoing parts				units
NZL1 (entity # 1)	30000	30000	30000	
NMF1 (entity # 2)	30000	30000	30000	
NAS2 (entity # 3)	30000	30000	30000	
NSG2 (entity # 4)	30000	30000	30000	
UGP1 (entity # 5)	30000	30000	30000	
Leistungsteil (entity # 7)	30000	30000	30000	
Leistungsteil + Steckbox (entity # 8)	30000	30000	30000	
IZL1 (entity # 10)	30000	30000	30000	
ILT1 (entity # 11)	30000	30000	30000	
ISG1 (entity # 12)	30000	30000	30000	
Steckbox (entity # 13)	30000	30000	30000	
Finished product (Steuerung_entity # 9)	30000	30000	30000	units
Undetected defects at LTT (Schlupf)	12	22	16	units
Undetected defects at LTT (Schlupf in %)	0.04	0.07	0.05	%
Undetected defects at SB (Schlupf)	294	220	206	
Undetected defects at SB (Schlupf in %)	0.98	0.73	0.69	%
Undetected defects at FP (Schlupf)	296	239	216	
Undetected defects at FP (Schlupf in %)	0.99	0.80	0.72	%
Undetected defects to customers (Schlupf)	81	99	87	
Undetected defects to customers (Schlupf in %)	0.27	0.33	0.29	
Avg. value-added cost	229.51	229.54	229.05	€
Avg. non value-added cost	509.65	508.63	509.86	€
Total cost	739.16	738.17	738.91	€
Avg. flowtime IZL1 (entity #10)	12.238	12.191	12.21	hour
Avg. flowtime ILT1 (entity #11)	12.238	12.191	12.21	hour
Avg. flowtime ISG1 (entity #12)	12.238	12.191	12.21	hour
Avg. flowtime_Leistungsteil	1.6109	1.5939	1.5949	hour
Total avg. flowtime for Leistungsteil	13.8489	13.7849	13.8049	hour
Avg. flowtime_Steckbox (entity 13)	12.683	12.619	12.638	hour
Avg. flowtime_Leistungsteil + Steckbox	1.3132	1.3307	1.3325	hour
Total avg. flowtime for Leistungsteil + Steckbox	15.1621	15.1156	15.1374	hour
Avg. flowtime NZL1 (entity 1)	15.163	15.116	15.137	hour
Avg. flowtime NMF1 (entity 2)	15.163	15.116	15.137	hour
Avg. flowtime NAS2 (entity 3)	15.163	15.116	15.137	hour
Avg. flowtime NSG2 (entity 4)	15.163	15.116	15.137	hour
Avg. flowtime UGP1 (entity 5)	15.163	15.116	15.137	hour
Avg. flowtime_Steuerung	1.3857	1.3882	1.39	hour
Total avg. flowtime for finished product	16.5487	16.5042	16.5274	hour

	Experiment 1	Experiment 2	Experiment 3	
Defects				
Leiterplattenfehler mechanisch	356	660	361	units
Leiterplattenfehler elektrisch	332	594	365	units
BE fehlt	460	684	435	units
BE falsch Typ/Wert	350	625	358	units
BE kein Kontakt	500	819	480	units
BE Kurzschluss	120	232	151	units
BE verpolt	137	226	149	units
BE defekt	219	344	225	units
diskrete / passive BE fehlt	211	369	221	units
diskrete / passive BE falscher Typ/Wert	234	350	189	units
diskrete / passive BE Position	211	332	257	units
diskrete / passive BE kein Kontakt	338	617	370	units
diskrete / passive BE Kurzschluss	130	208	136	units
diskrete / passive BE verpolt	366	589	354	units
diskrete / passive BE defekt	60	111	75	units
IC falscher Typ/Wert	534	1009	578	units
IC verdreht	606	974	576	units
IC Position	144	242	162	units
IC kein Kontakt	562	1015	586	units
IC Kurzschluss	860	1491	857	units
IC defekt	71	131	69	units
Übergangswiderstandsfehler	341	335	344	units
Isolationsfehler	326	356	381	units
Grenztemperaturfehler	345	337	318	units
Schnittstellenfehler BUS und Digital/Analog EA	1215	1163	1239	
Unterlagenfehler	612	652	513	units
Montagefehler	2620	2346	2217	units
Gehäuse fehlerhaft	672	545	577	units
Kennzeichnungs fehler	1456	1217	1297	units
Verdrahtungsfehler	2337	2016	2080	units
Sicherheitsrelevante Funktionsfehler	1028	868	903	units
Komponente defekt	581	445	426	units
statische Funktionsfehler	479	361	368	units
Echtzeitfehler	9	10	13	units
andere Fehler	604	578	486	units
Total	19426	22851	18116	units

	Experiment 1	Experiment 2	Experiment 3	
Processes				
IN				units
SMD Bestückung und Lötén	240000	240000	240000	
Bedrahtete Bestückung und Lötén	240000	240000	240000	
Sichtprüfung	240000	240000	240000	
Rework Sichtprüfung	736	1238	738	
AOI	240000	240000	240000	
Rework AOI	3849	6538	3989	
ICT	240000	240000	240000	
Rework ICT	2092	3493	2083	
Boundary Scan	0	0	0	
Rework Boundary Scan	0	0	0	
Dynamischer FKT	0	0	0	
Rework Dynamischer FKT	0	0	0	
Programmierung	240000	240000	240000	
Montage (Frontplatte)	180000	180000	180000	
Sys-FKT	240000	240000	240000	
Rework Sys-FKT	285	447	252	
ESS	240000	240000	240000	
Rework ESS	73	187	100	
Aufbau mit Leistungsteil	30000	30000	30000	
Sichtprüfung - Leistungsteil	30000	30000	30000	
Rework Sichtprüfung - Leistungsteil	2790	2018	2097	
Automatischer Sys-FKT_Leistungsteil	30000	30000	30000	
Rework Automatischer Sys-FKT_Leistungsteil	2194	1675	1647	
Steckboxeinbau	30000	30000	30000	
Bestückung der Steckbox	30000	30000	30000	
Konfiguration der Steckbox	30000	30000	30000	
Sichtprüfung - Steuerung	30000	30000	30000	
Rework Sichtprüfung - Steuerung	2973	2982	3077	
Sicherheitsprüfung	30000	30000	30000	
Rework Sicherheitsprüfung	1001	1022	1034	
Automatischer Sys-FKT_Steuerung	30000	30000	30000	
Rework Automatischer Sys-FKT_Steuerung	1963	1917	1885	
ESS - Steuerung	30000	30000	30000	
Rework ESS - Steuerung	121	100	117	
OUT				units
System out	30000	30000	30000	