Integrated Simulation Tool for Quality Support in the Low-Volume High-Complexity Electronics Manufacturing Domain

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Integrated Simulation Tool for Quality Support in the Low-Volume High-Complexity Electronics Manufacturing Domain

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Low-volume high-complexity printed circuit boards manufacturing is a highly dynamic domain because of prevailing global pressures. In such an evolving environment, quality issues caused by manufacturing defects are the major concern. The generation, detection and elimination of those defects further impact customer requirements and demands. Current practices in terms of identification and solution of quality issues have three major drawbacks: (i) the metrics used are not meaningful, (ii) several manual operations are involved and (iii) there is not significant decision support. A novel integrated simulation tool for quality support in the low-volume electronics manufacturing that overcomes these weaknesses is presented in this paper. The simulation tool supports current needs in the domain i.e. knowledge capitalisation, waste reduction, right-first-time performance and agility, as well as the domain customer requirements i.e. lead time, cost, quality and reliability. Quantitative results from a case study are presented as evidence of the usefulness of the tool in a real context. The results show that approximately 80% non-value added cost in the product studied is due to just two types of manufacturing defects. This outcome is key for root cause analysis based not only on defect quantity.

Keywords: *electronics manufacturing, integration, PCA, process modelling, quality, simulation.*

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1. Introduction

Over the past decades, increased competition, dynamic markets, government legislation and the need for fast innovation have put pressure on the electronics manufacturing industry (Zhang, Kuo et al. 1997), forcing companies to cope with continuous change. Companies located in western Europe and the United States have focused on markets supporting high value added applications e.g. military, aerospace and innovative prototypes (Chan and Spedding 2003) which are characterised by low production volumes and high product mix and complexity (Lambert, Abdunour et al. 2005). In this context, the customer imposes demanding requirements i.e. low lead times, low cost, high quality and high reliability (Niazi, Dai et al. 2006).

To improve or maintain the productivity and performance, while responding to continuous change (Quinn, Causey et al. 1997), companies in this domain need to be capable of formalising and reusing the knowledge and information generated, reducing the waste incurred while manufacturing a product, performing any action right first time, and supporting an effective reaction to market changes (Gunasekaran 1998). In addition, analysis and visualisation software tools play an important role in achieving these needs (Helo 2004). These tools need to provide feedback that supports fast and effective responses to variations and issues in a manufacturing system, thus reducing any negative impact and improving its performance.

Quality issues in terms of manufacturing defects is one of the major concerns in printed circuit assembly¹ (PCA) manufacturing since they increase the product lead time and cost and can decrease product reliability (Dusek and Hunt 2003) due to extra activities during detection and further elimination of the defects. Although some software tools have been developed to support this problem (Palaniswami and Hassan 1988; Senechal and Tahon 1998; Spedding and Sun 1999; Chan and Spedding 2001; Chan and Spedding 2003; Siemiatkowski and Przybylski 2006; Tan, Shen et al. 2007), they fail to cover the complete range of issues i.e. time, cost and reliability. A computational tool is presented in this paper as an integrated approach to enable the evaluation of quality issues impacts on time, cost and reliability. The tool can provide meaningful performance metrics and replace expensive manual activities by automatically supporting defect data analysis. This paper is organised as follows. Quality issues in PCB assembly are described in Section 2 together with the current and the proposed approach to their evaluation. Related work on simulation tools for quality issues assessment and their solution are presented in Section 3 along with a discussion of the gap that is to be addressed within this study covering the complete range of customer requirements i.e. lead time, cost, quality and reliability and using a more detailed and consequently more accurate model. The methodology followed to develop the computational tool is illustrated in Section 4, whilst a case study and the respective results are presented in Section 5. Finally, a brief discussion is given in Section 6.

2. Quality issues in electronics manufacturing

The biggest problem facing electronics manufacturing in the low volume domain is the reduction of the product quality as a consequence of defects generated during manufacturing processes (Fidan, Roush et al. 2006). A brief description of the manufacturing defects evolution is presented as follows (refer to Figure 1).

Figure 1 Evolution of manufacturing defects as a quality issue

¹ Printed circuit assembly refers to the set of a printed circuit board and its corresponding components to form the final product.

A. Generation

Defects in a printed circuit board assembly (PCA) can come from design features, components, bare boards, materials or be generated during the manufacturing processes. A typical PCA can include surface mounted devices (SMD) and can also include some plated through hole (PTH) components. Different studies show that the majority of the manufacturing defects (approximately 86%) on a PCA are generated in the three SMT processes i.e. printing, placement and reflow (Dusek and Hunt 2003).

Commonly, the generation of a defect is due to parameters associated with the process, the resources involved and/or the materials used. For instance, for the printing process, feasible causes of defects include variation in parameters such as printing speed and squeegee pressure e.g. if the squeegee pressure is very low, the solder paste might not fill in the stencil aperture ultimately resulting in an unsoldered joint (refer to Figure 1a)

B. Detection

In an ideal situation, manufacturing defects are detected so that the product can be repaired or scrapped in the worst case scenario. The detection is done at various inspections (e.g. manual visual inspection, automatic optical inspection (AOI) and 3D solder paste deposit profiling such as. Synapse Imaging In-line Solder Paste Inspection) and functionality tests (e.g. flying probe test (FPT) and integrated circuit test (ICT) located at different stages within a production line. Detailed description of these tests can be found elsewhere, (Freeman and Foust 1997), (Lawlor-Wright and Gallagher 1997).

Multiple inspection and test stages are a common strategy to inspect and detect all the types of component and their associated defects. The detection of a defect depends on the defect type, the component package, the inspection or test equipment and the location of the equipment within the production line. For example, an unsoldered joint in a peripheral leaded component could be detected by a superficial image comparison in the AOI machine as shown in Figure 1b. However, if the component is an area array type such as a Ball Grid Array (BGA), an optical plan area image would not detect an unsoldered joint. Detected defects are normally recorded in order to support root cause analysis based around defect quantity.

C. Elimination

Most of the manufacturing defects detected are repairable, although some extreme repairs might not be cost effective to undertake (e.g. rework of BGA's). The elimination of a defect depends on the defect type and component package. Whilst some defects might need a component replacement, others would need just a single joint to be reflowed via a manual soldering process. However, rework processes usually include additional soldering operations that can affect the reliability of solder joints possibly inducing latent fatigue cracks (Lea 1990) (refer to Figure 1c).

3. Related work

Simulation tools for manufacturing support can be classified into manufacturing system design and manufacturing system operation (Smith 2003). Several studies have presented manufacturing system operation simulation for performance analysis e.g. (de Souza and Zhang 1996; Kendall, Mangin et al. 1998; Rasmussen, Savory et al. 1999) and a number of authors have focused their efforts on supporting the assessment from a quality perspective (Table 1).

Palaniswami and Hassan (1988) developed a simulation model that enables the evaluation of different manufacturing scenarios assessing manufacturing cost and quality. The model takes into account each unit (product) independently so that more detail and accuracy are achieved (e.g. the cost of repairs depend on the number of defects in each product). However, this study does not provide a measure of the quality cost and the defect through detection and repair times.

Senechal and Tahon (1998) integrated activity based costing (ABC) (cost estimations based on the duration of activities (processing times)) and DES using an object oriented simulation package i.e. MODSIM II®. Although the outputs of the model are not specified, the figures and the mentioned customer expectations indicate that they were evaluated in terms of lead times, cost and quality. However, no quantitative results and the structure of the model used are given.

Spedding and Sun (1999) highlighted the affinity between ABC and DES. They implemented various case studies using WITNESS (Witness 1996) (a visually interactive simulation software) for PCA production. One of the case studies illustrates how their studied approach can support decision making in terms of inspection strategies. Two scenarios, with inspection stations at different locations, were assessed giving cost and quality metrics.

Chan and Spedding (2001, 2003) developed a quality assessment ABC-DES tool that evolved into IMPIM (Integrated Multidimensional Process Improvement Methodology). Defect rates and manufacturing information (e.g. processing times) were inputs. Their integrated approach gives results in terms of productivity, cost and quality. Other models were also studied and their simulation results were used to develop a neural network meta model (NNM) to support decision making.

More recently, (Siemiatkowski and Przybylski 2006; Tan, Shen et al. 2007) have published similar approaches with equivalent performance metrics. However, these studies do not take into account defect data with enough detail to provide accurate results i.e. defect classification and description. Moreover, the available simulation models do not appear to provide any results in terms of impact on reliability as one of the customer requirements.

In the following sections, the development and deployment of the CLOVES simulation module is presented. The tool addresses the gap that the literature review reveals in terms of: (i) completeness of the analysis and (ii) level of detail in the analysis. To achieve completeness, the tool provides performance metrics for all the domain requirements identified (i.e. lead time, manufacturing cost, product quality and reliability) by using comprehensive historical defect data, and the use of accurate enterprise models generated using CIMOSA and translated into DES models.

4. Method

This study presents a simulation-based integrated computational tool. The tool enables to model and simulate quality-based scenarios to provide performance metrics in terms of the domain requirements. The tool is part of a knowledge-based tool: CLOVES (Complex LOW Volume Electronics Simulation) which supports other issues in PCA manufacturing such as defect data input, knowledge formalisation and reuse, information systems integration (Figure 2).

Figure 2 Proposed approach for the evaluation and solution of quality issues

The main steps that the end-user should follow to implement the integrated simulation tool provided, are presented in this section. These steps are: (i) the formalisation of the knowledge to obtain the static models, (ii) the generation of the dynamic models and (iii) the simulation execution (see Figure 3). Before running the simulation, an optional step is the configuration of the models to suit a particular manufacturing system. Although it does not make part of the simulation tool, a posterior analysis of the results should be performed. The inputs of the simulation are predictive statistical models generated from historical defect data. These statistical models represent the generation of manufacturing defects within the simulation model. Other analysis and evaluation techniques are integrated within the simulation model i.e. activity-based costing (ABC), physical models and knowledge-based rules. The resulting integrated software tool enables complete

and accurate assessments of quality issues in the PCA. The performance metrics used to perform the evaluation are given in terms of lead-times, manufacturing cost, quality and reliability. The elements that constitute the simulation model enabling the achievement of the research objectives are presented in the next subsections.

Figure 3 Methodology

4.1. Process models

In terms of the process models, the static models were specified in terms of CIMOSA (Computer Integrated Manufacturing Open System Architecture) constructs and then translated into the dynamic models (simulation) in Arena®. The simulation model components are equivalent to the elements required to generate the process models for each product i.e. processes, sequences and resources. The static CIMOSA models contain all the information needed for the translation of resources names, resources cost, process names, resources involved in a process, and process times. The translation of CIMOSA business rules into the simulation model required some effort to be translated graphically as decision rules in the dynamic model. Some representative examples of static components and their dynamic counterparts are presented in Figure 4. The translation of static to dynamic models was a simple process, although it required some time as it is a manual process. The need for the development of translation tools that provide a direct mapping from process modelling to simulation models is evident as it has already been suggested in the literature (Klafehn, Weinroth et al. 1996; Baines, Harrison et al. 1998; Hernandez-Matias, Vizan et al. 2006).

Figure 4 Static model mapping into simulation model – examples

The nuclear unit of the simulation models proposed is a product. For a particular product to be simulated, these models described the processes, activities, their sequence and the resources involved. These three elements were essential for the implementation of the simulation model. Processes and sequences defined the manufacturing course of action to fabricate a product. Integration of resources was essential because the resource utilisation is the main driver of the product cost. The CIMOSA functional view provided models with these components. An example of the activity diagrams used as process models is shown in Figure 5. The diagrams specify a set of processes in the manufacture of a product. It also represents the sequence in which the processes are performed and the resources (human and physical) involved.

Figure 1 CIMOSA activity diagram: AOI inspection

4.2. Integrated models

The process model constitutes the basics of the simulation tool. The integration of a set of models is what transforms a common process simulation into a functional tool that provides highly detailed, complete and meaningful results in terms of the effects of manufacturing defects. The integrated models can be divided in two categories: (i) statistical models (i.e. generated from defect data) and (ii) knowledge-based models (i.e. rule-based models).

4.2.1. Statistical models of defect occurrence

In order to estimate the impact of manufacturing defects, the detection and elimination processes are simulated. These processes correspond to inspection, test and rework. The manufacturing processes, where the generation of the defects occurs, are not included in the simulation model. Instead, the generation of the defects is reproduced using statistical models of the defect occurrence. These models are derived from defect

data previously collected (i.e. historical defect data). In general, the manufacturing companies keep records from defects occurred in the past. These data usually includes the type of the defect and its location. However, the structure and the level of detail vary from one company to another.

4.2.2. Knowledge-based models

Three knowledge-based models were used within the simulation (see Figure 6). Given the nature of these models, they are specific to the domain in which the research is focused i.e. PCA manufacturing. The first two models shown in the Figure 6 are rule-based. These models describe behavioural rules for process workflow and also encapsulate expert knowledge in terms of the inspection and test equipment capability and the rework process functional character. For the dynamic model two sets of rules were used: (i) defect detection rules and (ii) rework process rules. Defect detection rules determine if a defect can be detected depending on the defect type, component package and monitoring equipment (see Figure 6a). The rework processes rules allow calculate the rework process time and the number of thermal excursions involved in the operation (see Figure 6b). This information was used as input to the physical model concerning and the likelihood of deteriorating the reliability of the product.

Figure 2 Knowledge based models description

The physical model relating the impact of the rework soldering operation to the product reliability used in the simulation tool was developed by (Lea 1990). The model enables the incremental number of visible cracks in a solder joint ΔJC caused by one thermal excursion that last certain time t_r at a certain temperature T_r to be determined (see Figure 6c). The model assumes that the assembly is thermally cycled (N cycles) at a certain point after the rework process. This is true in general since PCAs are thermally cycled at the final stage of the manufacturing process to reduce infant mortality (Plumbridge, Matela et al. 2003). The model also includes a constant A and the activation energy for the join degradation Q , which depend on parameters of the board and the thermal cycle process. The values used for the simulation model were taken from Tarr (n.d.) that presents values of ΔJC depending on discrete values of temperature and time (see Table 2).

4.3. Outputs

After a manufacturing model is completely specified in terms of the simulation model, the simulation is ready to be executed. The integrated models are already embedded in the simulation tool and are executed according to the process model. After the simulation is executed, a report is automatically generated by the simulation tool. The report contains the results of the simulation in terms of the impact of the manufacturing defects in a particular product in terms of time, cost, quality and reliability. The main results are displayed in various charts and tables that provide the appropriate visualisation of the effects, taking into account the objectives of the tool. The main elements in the report include:

- Average value added and non-value added time per product
- Average value added and non-value added cost per product
- Average value added time per process per product
- Average non-value added time per process per product
- Average value added cost per process per product
- Average non-value added cost per process per product
- Non-value added cost per defect type
- Defects per unit (DPU), defect per million opportunities (DPMO) and undetected defects, per defect type

- Percentage of products affected in terms of reliability

These results provided by the simulation tool support the root cause analysis by prioritising the quality issues and showing trends that are useful as a guide. It is important to reiterate that these results correspond to the effects of having manufacturing defects in a product, and not to overall estimates. For example, the meaning of the value added time per product given is the amount of value added time invested in detecting and eliminating the manufacturing defects in a product, to reassure its final quality. This value does not represent in any way the overall estimate of the value added time invested to manufacture a product and should be taken into account when analysing the results.

5. Case study

A case study was implemented based on a real product of a UK-based PCA manufacturer to illustrate the operation of the simulation tool in a real industrial scenario. The company studied is an original equipment manufacturer (OEM) for aerospace and defence applications. As it is common in this kind of industry, it handles a low volume and high variety production. Additionally, given the applications of the company, the products are high value added and highly complex. The characteristics manufacturing environment in this company (i.e. highly dynamic processes, and complex products) have several implications on the simulation models. For example, the generation of manufacturing defects on the products tends to be high due to large manual handling hence, product and process performance is affected. In this context, manufacturing defects represent a serious quality issue, and its solution is of chief importance.

5.1. Simulated manufacturing system

The system to be simulated corresponds to the first stage in the manufacturing process of one of the products in the company (i.e. surface mounted processes). The product selected is one of the PCAs that make part of an end product for aerospace controlling applications. As determined by the methodology illustrated in Figure 3, the first step is the generation of the static models of the manufacturing system to be simulated. This system consists of the surface mount processes for the product selected and the corresponding inspection, test and rework processes. These processes are represented in Figure 7 by a block diagram. The figure also shows the static model correspondent to the manufacturing processes, as well as to the inspection, test and rework processes.

Figure 7 “as-is” scenario, structure and examples

The actual manufacturing processes were modelled by means of the statistical models. These models were derived from a set of historical data obtained directly from the company. The data set corresponds to recorded information in regards to real defects detected during 50 weeks of production. Each record in the data contains information about the defect type, the component package, and the number of defects per component. Given the discrete nature of a defect event, the resulting models are discrete probabilities that indicate the likelihood of a particular defect occurring on a product. The resulting probabilities are presented in Figure 8. The figure shows the user interface that enables the user to insert the values into the simulation tool.

Figure 8 Statistical models, graphical user interface and example

The inspection, test and rework processes involved in the manufacture of the selected product are: (i) automated optical inspection (AOI), (ii) AOI rework, (iii) flying probe test (FPT), (iv) FPT rework, (v) in-circuit test (ICT) and (vi) ICT rework. The processes modelled are defined either as value added (VA) processes or as non-value added (NVA) processes. Value in this context has been defined as “a property of a product or service that the customer cares about and would be willing to pay for” taking the definition from (Whicker, Bernon et al. 2006). In this case study, the inspection and test processes were defined as VA processes, while rework processes were defined as NVA processes. This differentiation was made under the assumption that the customer would be willing to pay for inspection test where the quality of the product is assured and not for rework operations that represent a loss for the company. The CIMOSA models, including processes, processing times (probability distribution), process allocation and resources involved, are shown in Figure 9. The cost values are not given for confidentiality reasons. The time values are generally given by probability distributions. In this case, triangular distributions were used (i.e. TRIA(minimum, average, maximum) times observed. In the case of the rework processes, the times were assigned as initial null value. These values were modified during the simulation according to the knowledge methods. The detection rules were used for each inspection and test process. Rework process rules and the rework physical model were used for the re-soldering processes.

Figure 9 “as-is” CIMOSA simplified activity diagram

5.2. What-if scenario

What-if scenarios allow decision makers to evaluate variations in the real manufacturing models. Examples include using a different workforce distribution policy, a modification in the products design and the adoption of a new technology for a process).

The what-if scenario evaluated in this study corresponds to a change in resources at the inspection stage (refer to Figure 10). It is well known that most of the defects in a SMT production line for PCA manufacturing are generated during the printing process (Dusek and Hunt 2003). For this reason authors have proposed to perform AOI inspection after the printing processes. Following these ideas, a “what-if” scenario was defined then by relocating the AOI inspection process after printing and before placement. Hence, any rework process corresponds to washing away any misprinted solder paste. If this scenario is deploy in real practice in the company, an investment of a high pressure spray system at around £45k is required. However, a reduction of 15 minutes of the rework cycle times would be achieved and all the defects would be eliminated at once.

The purpose of the evaluation of this “what-if” scenario is to know if the changes and investments are cost effective in terms of product lead time, cost, quality and reliability. This situation is evaluated using the simulation tool to analyse the behaviour of the system model due to the changes.

Figure 10 “what-if” scenario definition

The implications of the “what-if” scenarios, in terms of the knowledge-based models are the following. In regards to the defect generation, the printing defects must be generated at the beginning of the simulation, separately from the rest of the defects that are generated after the AOI inspection. For this reason the defect data available are classified according to the defect types. It is assumed that the defects generated in the printing process are those related to the solder paste volume (i.e. not soldered, solder bridge, insufficient solder and excess solder). Although the assumption is not strictly consistent with the reality, it is a good approximation and enables a relatively accurate evaluation.

The inspection and test equipment remain unchanged, hence the defect detection rules stayed the same. In contrast, the rules that define the time and activities related to rework processes (i.e. mainly in terms of thermal excursions) vary significantly particularly for the AOI rework process. This variation results from the change in the location of the correspondent inspection processes, and the consequent change of equipment. Hence, the rules that determine the time and number of thermal excursions for the process were modified. To validate and verify the what-if model, the implementations were revised and checked for logic consistency. Before running the definite execution of the simulation models, all the stochastic variables were replaced by deterministic values to validate the models comparing with manual calculations. The consistency of the simulation outputs (see section 4.3) with the real values was probed. After confirming the validity of the models, the results for the case study were obtained. These results are presented in the following section.

6. Results

The results generated by the simulation tool presented are given in terms of lead time, cost, quality and reliability. The output of the simulation is tightly related to the technical focus of this research, which is the effect of quality issues in the product and the processes performance. Consequently, the values reported by the simulation tool correspond to the detection and elimination of manufacturing defects. This is the impact of defects in terms of time, cost, quality and reliability. The values provided do not correspond to overall estimations for a product. For instance, an obtained time value represents the additional time investment caused by a defect, instead of an overall estimation of the product lead time. All the cost results are given in percentage. Time and cost results were classified in value added (VA) and non-value added (NVA) as discussed previously (refer to Figure 11a for time and to Figure 11b for cost). Figure 11a represents the average lead time of a product for the simulated batch and Figure 11b the same metric in terms of cost. Figure 11c and Figure 11d are the equivalent charts for the “what-if scenario”. The time invested detecting and eliminating the manufacturing defects, for a given product in the real scenario, is predominantly NVA time (see Figure 11a). In this case, the NVA time includes, not only the processing time in NVA processes, but also the time that a product is waiting to be processed. The VA cost represents the major contribution to the product cost in this stage, although it is significant that approximately 40% of the cost is in NVA processing (see Figure 11b). The NVA time and cost should be used as metrics to assess any corrective action on the quality of the product with the ultimate target to reduce them to zero.

Figure 11 VA/NVA time and cost per product

The time and cost results represent the first evidence given to the decision maker to evaluate the “what-if” scenario proposed. In terms of time (see Figure 11c) the VA time contribution remains constant, but the NVA time is almost halved compared to the real scenario. The reduction in NVA cost contribution to the detection and elimination of manufacturing defects in a product is also reduced as shown in Figure 11d. This figure presents the differences in terms of relative contributions. If the real values are taken into account, a reduction of approximately 52% in the NVA cost invested in the product can be calculated. The NVA cost as classified by defect type is illustrated in Figure 12a and Figure 12b for the as-is and what-if scenarios respectively. It can be seen that currently, almost 80% of the NVA cost is incurred repairing just two types of defects i.e. reversed polarity and misplaced components. This result represents an important guide for the root cause analysis, suggesting a focus on these two defects given its impact on the product performance in terms of cost. The results in terms of percentage for the “what-if” scenario (see Figure 12b)

are not significantly different. The absolute values though, show that the total cost invested to repair all the defects is reduced to around 75% when the AOI inspection policy is changed as proposed (see Figure 12c).

Figure 12 NVA cost per defect type in % and absolute values

The quality results are given in terms of the metrics suggested by IPC standard (IPC 2002) i.e. defect category, defect per unit (DPU) and defect per million opportunities (DPMO). For these calculations was necessary to have available the number of defect opportunities within the particular product. These data were extracted directly from the bill of materials (BoM) of the product simulated. The number of opportunities defined by the IPC is grouped in defect category corresponding to (i) component, (ii) termination, (iii) placement and (iv) assembly. The placement opportunities correspond to the number of components in the product whilst the component opportunities correspond to the number of components plus one for the bare board that counts as a component. The termination opportunities are the total number of terminations on the PCB assembly i.e. solder joints. The assembly opportunities equal one for every PCB assembled. With these data, the DPMO metric is

$$DPMO_{Ct} = \frac{\sum D_{Ct}}{\sum O_{Ct}} \times 1000000$$

Where Ct stands for each defect category, DCt is the number of defects in a particular category and OCt is the number of defect opportunities for that particular category. The overall Defects per Unit (DPU) is calculated according to:

$$DPU = \frac{\sum D}{NBA}$$

Where D is the total number of defects per board and NBA is the total number of boards assembled. The results for the case study are presented in Table 3.

The criticality of the placement DPMO can be identified by its value, which is at least 10 times higher than the value for the rest of the categories taken into account. This information is consistent with Figure 12c where the most critical defects in terms of cost are placement defects (i.e. “reversed polarity” and “misplaced”). This guides the analysis of the results to focus not only on the components and type of defect (i.e. “reversed polarity” and “misplaced”) but also on the process where the defect might have occurred. Note: there is no guarantee that although the placement process is the most obvious source of these defects that it is the sole root cause of the problems. This section of the results corresponds to the defect generation and hence, it can be directly calculated from the defect data without using the simulation. For this reason the results for the “what-if” scenario in terms of quality are equivalent.

The final results are represented in terms of product reliability, which is the most customer sensitive metric as a target of the quality control in a PCA manufacturing company in the low volume and high mix electronics manufacturing domain. The product reliability deterioration resulting from rework manufacturing defects is illustrated in Figure 13. The results are presented in terms of visible cracks generated after rework operations according to the rework physical model used. Although the number of PCAs with fatigue cracks in the solder joints, as a result of rework operations approximately 10% of the batch according to the current state of the system (see Figure 13) they could possibly be shipped to the customer since the model predicts future cracks based upon post processing thermal cycling of the PCA. This could represent a catastrophic safety issue given

the applications in the domain e.g. military, aerospace. This critical percentage would be reduced to less than just a fourth if the inspection policy proposed by the “what-if” scenario would be implemented.

Figure 13 Impact on reliability due to manufacturing defects in terms of fatigue cracks

The results proved to be valuable as a guide to approach a root cause analysis and as evidence to support the decision maker in the evaluation of an alternative scenario. In the first place, it was identified that the detection and elimination of the manufacturing defects in the product studied imply high time and cost investments. This fact highlights the criticality of the defects that are usually generated during the current manufacturing process of the product. A further classification of the NVA cost per defect type enabled the prioritisation of the current issues. The quality results presented using the IPC standard metrics allowed to associate the most critical defects to a particular process i.e. placement. Finally, the possible impact of the current defects in terms of a detriment in the product reliability could be evidenced from the percentage of boards likely to have an undetected crack that could result in catastrophic in-service failures. Similarly, the evaluation of a feasible “what-if” scenario provided meaningful evidence of the benefits that the implementation of the new policy could bring to the company. Significant reductions in terms of the amount of NVA putted into a product to assure its quality were demonstrated. Subsequently, the cost of detecting and eliminating the defects generated during the current manufacturing processes for the product studied is proved to be reduced by approximately a quarter with the adoption of the new inspection policy. The final and most important result, taking into account the applications of the domain, is a sharp reduction in the percentage of boards likely to be affected in terms of reliability, from 10% to 2.5%.

6. Discussion

Given the characteristics of low volume electronics manufacturing domain (i.e. variability, complexity, high value added products), manufacturing defects represent a major issue. The current approaches found in the literature to solve this quality problem are ineffective. The main objective of the present study was to provide a simulation tool to address these problems. An integrated simulation structure was provided, which enables to evaluate the impact of manufacturing defect in the performance of the processes and the product. The tool supports the prioritisation of manufacturing defects and gives meaningful guides for a subsequent root cause analysis. The integration of knowledge-based models to a discrete event simulation model was also a key contribution of this work as it allowed to accurately estimating additional time, cost and deterioration of the product quality and reliability due to manufacturing defects. The evaluation of real scenarios and what-if scenarios, based on manufacturing CIMOSA models was possible and provided meaningful and complete results. Different scenarios can be evaluated supporting the decision-making before implementing the “optimum” of the alternatives i.e. “what-if” scenarios highlighting the risk that would be incurred in actually implementing any changes without previous assessment. In this way the tool can be used to evaluate and support the attainment of agility and change capability in a company (Gunasekaran 1999). The studied models were particular to a test strategy in the assembly of PCBs. Therefore the scope of the model is limited. The simulation model included the main inspection, test and rework processes but description of other manufacturing processes was not available. Additionally, even if the simulation model contained all the processes involved in the manufacture of a PCA such a model would have to be modified for every different product, since the processes involved are product dependent as it is usually the case for no-deterministic assembly processes.

7. Conclusions

Manufacturing defects generation in PCA production lines is the biggest problem in low volume and high mix electronics manufacturing. The software tool described in this paper provides modelling, simulation, analysis and visualisation capabilities in order to support the evaluation and solution of quality issues in terms of manufacturing defects present in the product. The simulation model is integrated with appropriate costing techniques, as well as rules and physical models to obtain performance metrics focused around the main customer requirements in the domain i.e. fast delivery time of low cost products with high quality and reliability. The results enable the user to evaluate actual and possible quality-based scenarios helping companies to cope with continuous change formalising the knowledge and information generated, reducing the waste, performing actions right first time and becoming more agile.

Similarly to the traditional approach to the solution of quality issues, the simulation tool presented prioritises quality issues and highlights trends. These elements are useful to guide the root cause analysis. Furthermore, the support and guidelines provided by the model-based approach are more meaningful since they are founded on performance metrics in terms of the domain customer requirements. The metrics obtained as outputs can also be used to support robust decision making between alternative scenarios. In addition, since the tool automates some of the tasks done within the traditional approach, it significantly reduces the time incurred from defect data capture to the generation of meaningful outputs.

Future work is currently being undertaken to enable: (i) a range of physical models to be linked to any process in the production and (ii) models of human resources and human product handling are included to generate a more complete range of opportunities for defect generation to be evaluated. These enhancements will support additional simulation functionality including detailed defect prediction, support for set up processes and process capability assessment.

Additionally, a generic configurable simulation that includes all the possible processes to manufacture a PCA is desired, such that it can be readily configured with any product and any variation in processing and workflow practices can be simulated and evaluated. The generic simulation will enable a large range of users within a particular manufacturing domain to obtain complete time, cost and reliability estimation, as well as to evaluate "what-if" scenarios at any point in the product lifecycle.

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Tables

Table 1 Classification of simulation tools for quality assessment

Reference	Domain	Integrated Techniques				Performance Metrics				Comments
		DES	ABC	Continuous Models	Statistical Models	Time	Cost	Quality	Reliability	
(Palaniswami and Hassan 1988)	Manufacturing	×					×	×		Use simulation to design and analyse manufacturing systems to achieve the most economical alternative.
(Senechal and Tahon 1998)	Manufacturing	×	×			×	×	×		Identify and provide lead time, cost and quality as the main customer expectations in the domain.
(Spedding and Sun 1999)	Manufacturing Electronics	×	×			×	×	×		Illustrate the affinity between DES and ABC to model manufacturing systems, showing the application to quality costing.
(Chan and Spedding 2001)	Manufacturing Electronics	×			×	×	×	×		Develop a quality assessment tool based discrete event simulation.
(Chan and Spedding 2003)	Manufacturing Electronics	×	×		×	×	×	×		Present a tool i.e. IMPIM that supports improvements of the processes in terms of quality with cost as a constraint.
(Siemiatkowski and Przybylski 2006)	Manufacturing Machining	×				×	×	×		Allocation of inspection operations based on operation efficiency and cost of quality.
(Tan, Shen et al. 2007)	Manufacturing	×	×			×	×	×		A simulation tool supports business process re-engineering through a dynamic process performance tool.
CLOVES Tool Kit Simulation Module	Manufacturing Electronics	×	×	×	×	×	×	×	×	The module is a simulation-based software tool to assess quality issues in a PCA production line. The results are given in terms of lead time, cost, quality and reliability

Table 2 Discrete values for Lea model, taken from (Tarr n.d.)

Rework Time	Rework Temperature		
	350 °C	400 °C	450 °C
2 sec	---	8.0%	---
4 sec	6.5%	8.5%	10.0%
6 sec	---	9.0%	---

Table 3 Quality metrics

IPC DPMO and Estimated Yield	
Component Opportunity	1344
Termination Opportunities	4248
Placement Opportunities	1343
Assembly Opportunities	1
Component DPMO	0
Termination DPMO	21.57
Placement DPMO	260.61
Assembly DPMO	0.00
Overall DPU	0.43

Figure 1 Evolution of manufacturing defects as a quality issue

Figure 2 Proposed approach for the evaluation and solution of quality issues

Figure 3 Methodology

Figure 4 Static model mapping into simulation model – examples

Figure 3 CIMOSA activity diagram: AOI inspection

Figure 4 Knowledge based models description

Figure 7 “as-is” scenario, structure and examples

Figure 8 Statistical models, graphical user interface and example

Figure 9 “as-is” CIMOSA simplified activity diagram

Figure 10 “what-if” scenario definition

Figure 11 VA/NVA time and cost per product

Figure 12 NVA cost per defect type in % and absolute values

Figure 13 Impact on reliability due to manufacturing defects in terms of fatigue cracks

Evolution of manufacturing defects as a quality issue
210x220mm (96 x 96 DPI)

Proposed approach for the evaluation and solution of quality issues
245x263mm (96 x 96 DPI)

Methodology
224x292mm (96 x 96 DPI)

Static model mapping into simulation model □ examples
252x313mm (96 x 96 DPI)

CIMOSA activity diagram: AOI inspection
211x129mm (96 x 96 DPI)

Figure 6 Knowledge based models description
256x164mm (96 x 96 DPI)

Figure 7 as-is scenario, structure and examples
249x219mm (96 x 96 DPI)

DISCOVER - Simulation input

Defect Models

	Probability	
	Analog, Signal Conditioning	Power Supply
Voids	<input type="text" value="0"/>	<input type="text" value="0"/>
Not Soldered	<input type="text" value="0.04"/>	<input type="text" value="0.1"/>
Solder Bridge	<input type="text" value="0.06"/>	<input type="text" value="0.275"/>
Insuficient Solder	<input type="text" value="0"/>	<input type="text" value="0.05"/>
Excess Solder	<input type="text" value="0.04"/>	<input type="text" value="0"/>
Poor Wetting	<input type="text" value="0"/>	<input type="text" value="0"/>
Solder Balls - Splatter	<input type="text" value="0"/>	<input type="text" value="0"/>
Tomb-Stoned	<input type="text" value="0.4"/>	<input type="text" value="0.1"/>
Lifted Pad	<input type="text" value="0"/>	<input type="text" value="0"/>
Missing	<input type="text" value="0.08"/>	<input type="text" value="0.125"/>
Wrong Part	<input type="text" value="0"/>	<input type="text" value="0.05"/>
Reversed Polarity	<input type="text" value="0.2"/>	<input type="text" value="0.125"/>
Missplaced	<input type="text" value="0.2"/>	<input type="text" value="0.2"/>
Other	<input type="text" value="0.04"/>	<input type="text" value="0.025"/>

Assembly Data

Size	Access	Coverage
<input type="text" value="Small"/>	<input type="text" value="1"/> %	<input type="text" value="1"/> %

Buttons:

- Load Data
- Change Data Interval
- Define Additional Inputs
- Run Simulation
- Options
- Exit

Figure 8 Statistical models, graphical user interface and example
224x294mm (96 x 96 DPI)

Figure 9 as-is CIMOSA simplified activity diagram
185x84mm (96 x 96 DPI)

Figure 10 □what-if□ scenario definition
250x123mm (96 x 96 DPI)

Figure 11 VA/NVA time and cost per product
185x143mm (96 x 96 DPI)

Figure 12 NVA cost per defect type in % and absolute values
254x91mm (96 x 96 DPI)

Figure 13 Impact on reliability due to manufacturing defects in terms of fatigue cracks
199x129mm (96 x 96 DPI)