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Flex-Eman
Flexible soldering cells for agile electronics manufacture

HORIZONTAL RESEARCH ACTIVITIES INVOLVING SMES
CO-OPERATIVE RESEARCH

D4: Final Project Activity Report
WP 1

Due date of deliverable: 15 April 2007
Actual submission date: Friday, April 13, 2007

Period covered: December 2004 to February 2007
Start date of project: 29 November 2004 **Duration: 2 yrs.**

Project Co-ordinator name: Mr. Steve Butler
Project co-ordinator organisational name: Planer PLC

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1 Publishable Executive Summary

The goal of Flex-Eman project is to develop and demonstrate a novel, scalable manufacturing technology of several Precision Reflow Soldering Chambers (PRSCs) arranged in a cell and supplied with products by means of an automated handling system. The integration of PRSCs requires intra-cell communication and supervision system as well as inter-cell communication with other facilities in the production environment. This scalable manufacturing technology should be cost effective for SMEs, capable of high quality manufacture, fault tolerant, eco-friendly, suitable for lead-free soldering and inherently agile to allow effective manufacturing of mixed product types and/or batch sizes. The project brought together SMEs and research organisations from four different countries resulting in a trans-national technical cooperation. The participants of the Flex-Eman project include Planer plc (UK), Seremap (France), Datalink (UK), FOAB Elektronic AB (Sweden), Realtime Technologies (UK), Custom Interconnect LTD (UK), MBDA UK, Loughborough University (UK) and Chalmers University of Technology (Sweden).

The major difficulty with introducing Flexible Manufacture to the electronics industry appears to have been the inflexibility of the solder reflow process. Much time is lost setting up a reflow oven for a different product and small batch sizes generally result in lower yields and inefficiency in energy consumption. Additional difficulties encountered are caused by the stringent process requirements brought about by lead-free soldering, which requires higher soldering temperatures, the use of an inert gas shield rather than air, and more accurate temperature control. Many existing reflow ovens are unable to cope with such process requirements and those that do tend to be high cost variants which are optimised for high volume production. Thus the need for a Flex-Eman system, abiding by the following specifications, can be seen:

- low capital costs,
- scalable production capacity,
- the capability to accept a high product variety,
- efficient soldering of mixed batch sizes, from single item to medium batch sizes.
- accurate temperature control (32 zone temperature control), particularly the cooling rates the products experience,
- minimum set up time between products,
- low consumption of inert gas during soldering, and
- low energy consumption.

The Flex-Eman system also provide remote monitoring and 3D visualisation of the operation (through a human machine interface - HMI) of the several PRSCs and automated handling system within the cell. The system is highly reconfigurable so that it can be scaled up or down to cater for different needs and production capacities. This provides the capabilities to facilitate remote diagnostics and maintenance of the system without shutting the whole system down. In-case of low throughput, or emergency, the automation handling system can be replaced by a manual operator.

The Flex-Eman research developed a ‘cookbook’ that provides guidelines in lead free processing issues, such as: inert gas consumption, process uniformity and accuracy of the thermal profiling and the affects of rapid cooling on the products and microstructures.

2 Summary of project activities

This section provides a summary of the activities carried out under each work package.

2.1 WP1: Project Management

Lead contractor: Planer
Participants: Serma, Datal, FOAB, Real, CIL, MBDA, LU and CU

This workpackage provided the project with management, quality control and a common framework in which partners can communicate efficiently and a base for monitoring overall progress of deliverables, costs and documentation. The secure web facility was used to share documents extract other partners' information, begin forums, follow the project plan - updating tasks and allowing real time conferences between partners as well as instant messaging.

2.2 WP2: System Specifications

This work package provided a preliminary understanding and guideline for the Flex-Eman cell. The envisaged automation system consists of a robot, column of stacked T-Track PRSC ovens and conveyors for PCB transportation. The automated Flex-Eman cell will have the capability to be monitored and controlled via an Ethernet network interface. A detailed system specification is documented in deliverable 5.

2.2.1 D5: System Specifications

- As outlined in the deliverable the Flex-Eman system should have the following features:
- The System should be reconfigurable so that it can be scaled up or down to cater to the different needs and production capacities of end-users.
- The System could be scaled down to consist of only the ovens and the conveyor system (without the robot) for scenarios where production capacity was small or throughput low. Automatic handling/loading of PCBs would be unnecessary in this case and be replaced by manual operator.
- The position of the robot to move to the input/output conveyors as well as the respective ovens must be reconfigurable (i.e. not hard coded) in order for the System to be reconfigured for different oven/system configurations.
- A human operator should be able to visualize the state of the operation and, in the case of manual operation, control the automation process through an Internet browser-based human machine interface.
- The System to be able to provide remote monitoring and 3D visualisation of the operation through the HMI. This provides the capabilities to facilitate remote diagnostics and maintenance of the System.

2.3 WP3: Business Processes

This workpackage involved the understanding of typical current manufacturing processes, formalising current processes and developing appropriate models (i.e. business processes and discrete event production simulations). Appropriate change scenarios and metrics were determined to enable the effect of change on the current process to be evaluated. The PRSC oven process was formalised and modelled and the same change scenarios applied to enable relative measures of “agility”, cost and time to be determined.

Within Tasks 3.3 and 3.4, to enable the development of an agile soldering cell, the required changes to the current practice were identified. Furthermore, the implementation issues regarding the compatibility of the proposed solution to the project collaborators’ businesses were also recognised. The new soldering system was designed and modelled as part of Task 3.5 and a set of What-If scenarios were exercised as part of Task 3.6. The findings of these tasks are documented in project following project deliverables:

- D7. Capture and representation of operation of current manufacturing process
- D8. Determination and modelling of impact of metrics and change scenarios
- D9. Evaluation modelling of PRSC system and automation scenarios

2.3.1 D7: Capture and representation of operation of current manufacturing process

To understand the impact of PRSC on the current collaborators businesses, it was necessary to initiate the research by understanding the way the soldering process is carried out and demonstrate a common model of AS-IS soldering processes that could be applied to all collaborators. A further TO-BE model of the PRSC system was also developed and compared with the initial AS-IS model to enable evaluation of system changes and requirements for implementing PRCS soldering concept.

The capturing method and demonstration of the systems were based on a standard enterprise modelling approach developed in Loughborough University. In this method, the captured knowledge from an existing system is formalised in an abstract format and a simulation model is developed to facilitate examining various “what-if” scenarios on the system. illustrates the modelling approach adopted in this research.

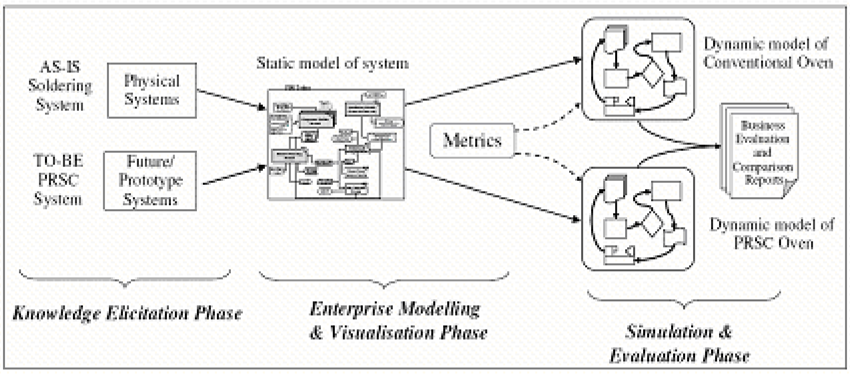


Figure 1: Modelling Approach Adopted in this research

The conventional and PRSC soldering ovens were demonstrated by static and stimulations models. The stimulation models enable the users to analyse the system specifications with various set of information customised for a collaborator businesses. For instance, the two soldering methods were compared based on their productivity (number of boards per shift), utilisation, time and energy consumptions.

2.3.2 D8:Determination and modelling of impact of metrics and change scenarios

The abstracts of the soldering systems were developed formally and simulation models were designed to enable customisation of model with different sets of production scenarios. This enabled comparisons between the current soldering systems and the proposed PRSC approach. The comparison was based on a number of criteria gathered from the project collaborators. These include: improve in flexibility, productivity, soldering precision, costs, and shop floor space. Figure 2 illustrates the TO-BE simulation model of the PRSC system.

A number of production scenarios were examined to assess the impact of changes on the soldering systems in respect with the above mentioned criteria. The scenarios were aimed to make some initial recommendations on the number of ovens required for each collaborator to maintain their existing level of production and cope with the future low volume/ high variety market demand. This would provide clear indication on technical and financial implication of adopting the PRSC soldering method on the current businesses.

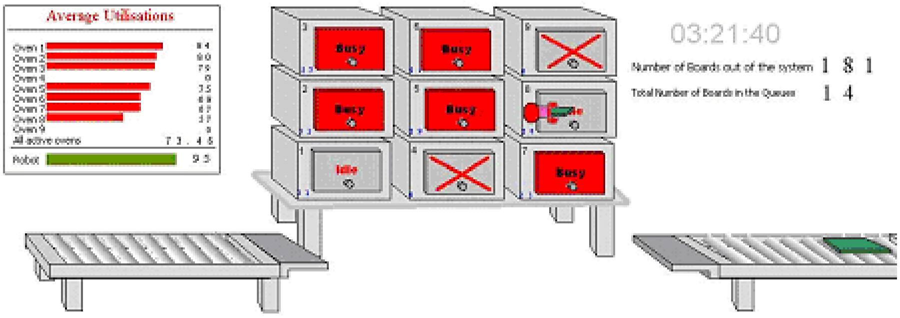


Figure 2: Simulation Model of the New Soldering Cell

Each collaborator have had opportunities to use the simulation tool based on their own customisation set, however a set of generic specification was developed based on the production scenario common for typical SME's business processes.

2.3.3 D9: Evaluation modelling of PRSC system and automation scenarios

A comprehensive assessment analysis was carried out to predict the impact of the new soldering system on various project partners.

The results of simulation runs were categorised into quantitative results and qualitative ones. The first type was supported by the outcome of the simulation models and the statistical analyses carried out following the simulation, whereas the second type was based on laboratories/shop-floor tests and experts' opinions.

To illustrate the extent of changes 3 different production scenarios were targeted, including: a) a high volume soldering of similar boards, b) a very low volume of highly mixed boards (random arrival of boards), and c) A typical production scenario suitable for the project collaborators (e.g. 250 boards of four different types per shift).

The results are discussed in details in deliverable 9. Samples of assessment results are graphically shown by Figure 3.

It was concluded as the results of this work package that the new soldering cell system can potentially help the European electronics SMEs to accommodate the new market requirements. However, the effectiveness of the system is expected to be significant only when dealing with highly differential customer orders.

Despite the reluctance of some of the partners to migrate to the new soldering method, it was concluded that considering the trend of the market change in Europe, need for some adjustment to the resources and machineries are inevitable, and the new soldering approach is envisaged to be an appropriate alternative to the current soldering approaches, especially within the lead-free soldering environment.

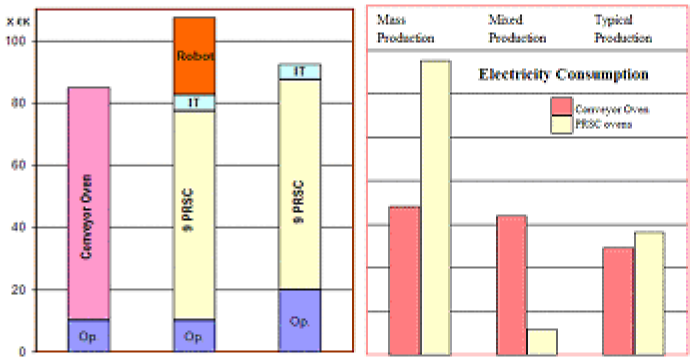


Figure 3: Sample of Assessment Results (Cost and Electricity)

2.4 WP4:Supervisory Control System

Lead contractor: LU
Participants: Planer and Serma

This workpackage addresses the detailed definition, implementation and test of a supervisory control system for the multi-oven PRSC implementation. The supervisory control system enables product identification, optimum profile selection, oven selection based upon user selectable strategies and monitoring of the system performance to be presented in appropriate user specified formats. Detailed description of the Supervisory Control Application and its sub-components are given in project deliverables 10 to 13:

- D10: Task control module for system integration
- D11: Graphical user interface for system integration
- D12: Oven selection module for system integration
- D13: SPC module

2.4.1 D10: Task control module for system integration

To enable integration of the PRSC control system and the associated IT support systems to the physical devices within the new multi-oven soldering system, a set of software modules were developed within WP4. The modules interact through an application tool System Integration Toolkit (SIT) providing interoperability of the modules, connectivity with the real world systems and human interactivity.

2.4.1.1 Supervisory Control Software

The Supervisory Control Application manages various sub-systems of the multi-oven PRSC system. The Supervisory Control Module (SCM) provides services for system configuration, emulation, visualisation, and monitoring and analysis. The SCM supports the following functions allowing a user to:

- define ovens selection strategies and priorities
- define the system control logic
- define board arrival input type
- run an instance of a system logic control
- simulate/visualise the physical and logical system
- record data production logs and statistical analysis of system activity

The SCM consists of a number of software modules which interact as illustrated in Figure 4:

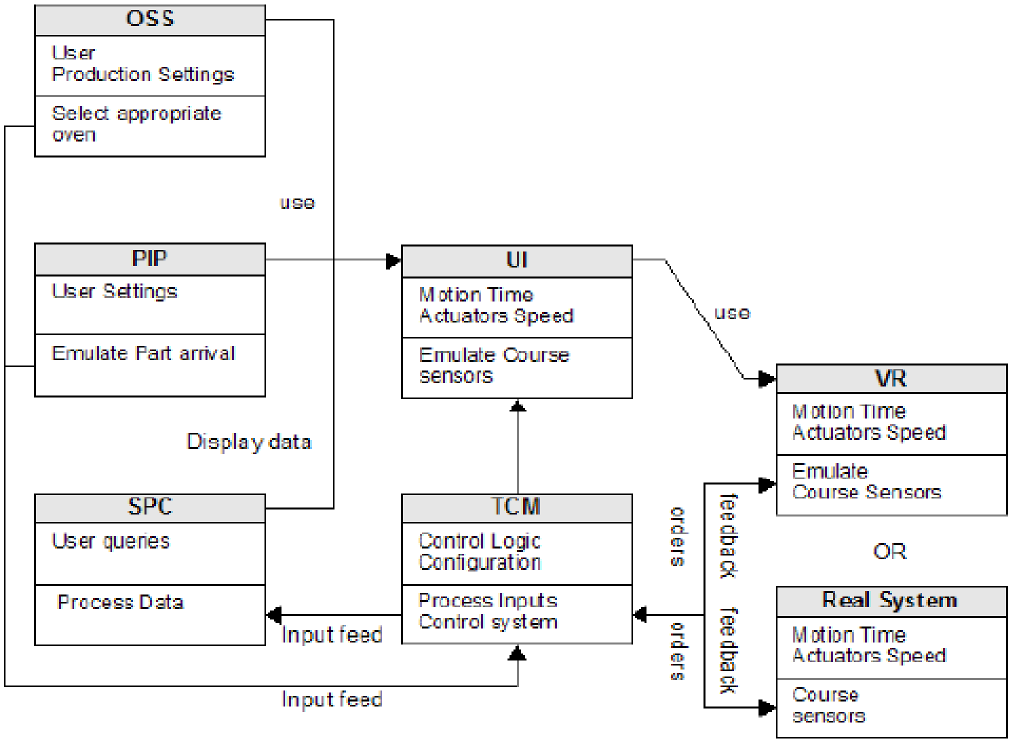


Figure 4: Supervisory Control Module

TCM module is presented in D10 but the GUI, OSS and SPC are reported in D11 and D12 and D13 respectively.

2.4.1.2 Task Control Module

The Task Control Module is central to the Supervisory Control application. It allows generating various system modules' static settings and live data to be synthesised into a coherent multi oven system control logic. The main TCM functions are:

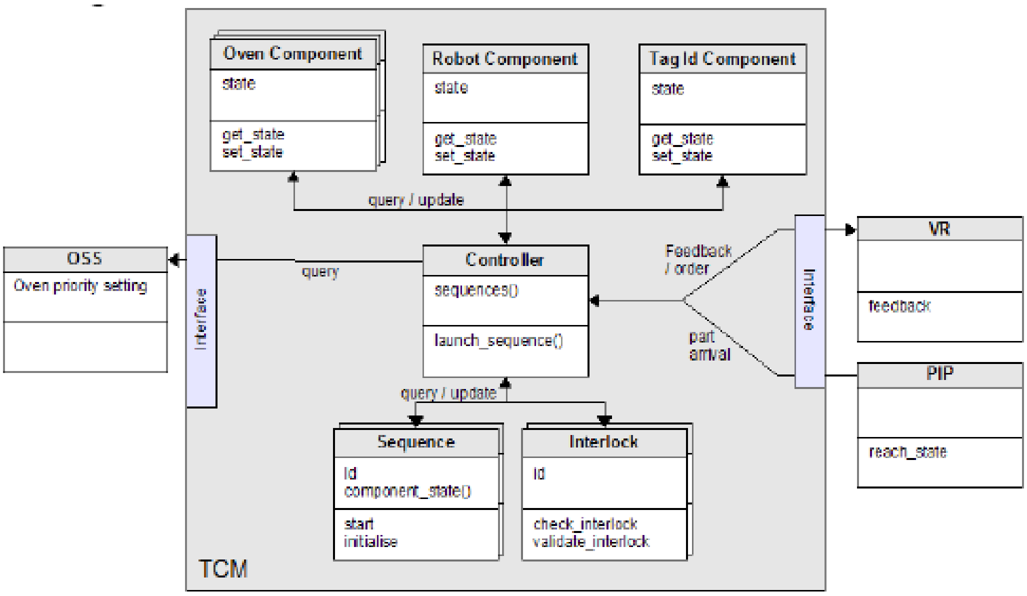


Figure 5: Task control module

- Host and manage various software components
- Host the definition of sequences as possible transitions between pre-defined system states. Also define the logical conditions of those transitions.
- Interface with the multi oven system other software modules
- Collect system feedback and generate control events based on components availability and user defined process strategies and priorities

The Task Control Module support several processes as described. Three distinctive sequences are:

- **Oven selection sequence**: TCM responds to a part arrival by checking oven availability. After oven selection the Controller either directly starts the loading sequence or waits for the selected oven to be available.
- **System state update sequence**: TCM responds to a change of system state by updating the states of the internal components corresponding to the real system.
- **Sequence control:** at each system state change event, TCM updates its internal interlocks table, and checks the running sequences.

2.4.1.2.1 TCM Graphical User Interface

The Task Control Module is built as part of the System Integration Toolkit (SIT). The illustration shows snapshots of the SIT application. Each module was designed independently and bound to each other by the SIT application. User can navigate through the various modules by using the provided interactive menu.

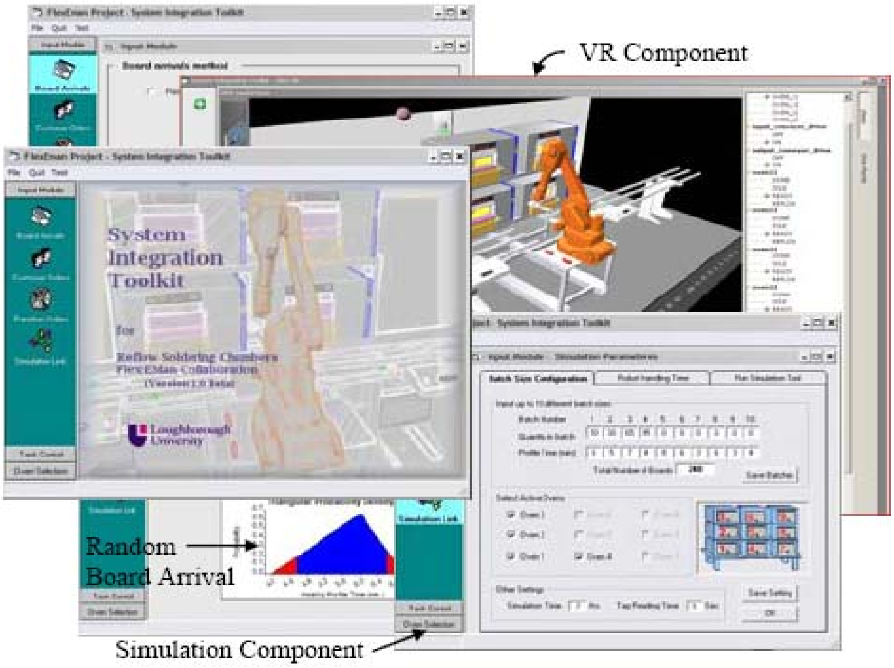


Figure 6: TCM Graphic User Interface

2.4.2 D11:Graphical user interface for system integration

The specification of the SIT application was described in D10 and M2. D11 focuses on the details of the Supervisory Control System of the SIT application.

The functions provided by the Supervisory Control Software (SCS) and its internal software modules including the Task Control Module are made available via a graphical user interface. The GUI prototype was implemented using Visual Basic UI controls and integration of a representation of the physical system implemented using Virtual Reality Modelling Language. 3D models provide an intuitive view of the system for cell configuration/reconfiguration and remote monitoring/ maintenance.

The main GUI windows can be decomposed into two main parts:

- The top part is dedicated to management, control and configuration of 3D models(4 & 5)
- The bottom part is dedicated to cell configuration, simulation and monitoring (1, 2 & 3)

The functions of the SCS to which the GUI provides access to, can be grouped in three main sets:

- Multi Oven System configuration/ reconfiguration
- Multi Oven System simulation/ monitoring
- Production process data visualisation/analysis (WP4.D13)

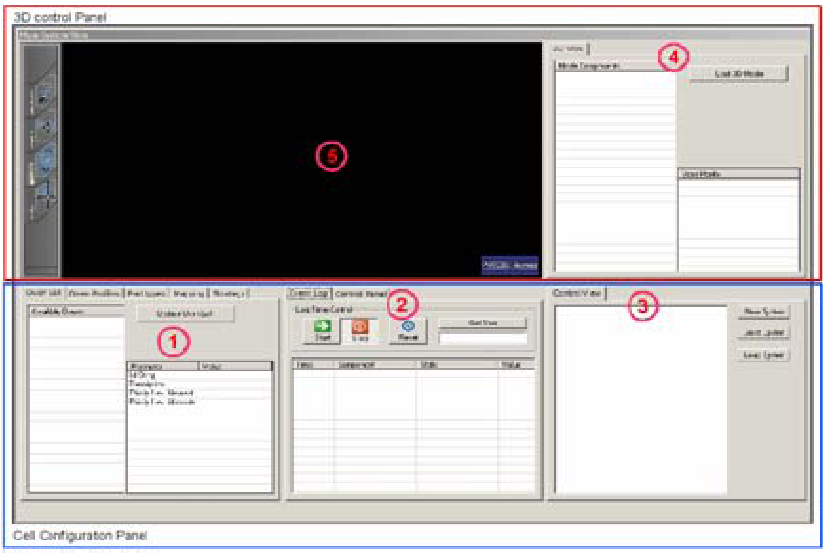


Figure 7: SCS GUI Overview

2.4.2.1 Multi-oven system configuration

The tasks associated with the configuration of a generic multi oven system have been defined using a basic cell configuration that includes (i) an n*n array of T-Track ovens, (ii) a conveyor system enabling the input, output and identification of part products, and (iii) a robot manipulator.Various cell configurations may need different or additional requirements regarding the implementation of the cell (re-) configuration process and associated SCS functions and GUI.

Typical tasks that should be conducted for Multi Oven system configuration/ reconfiguration have been defined as:

- describing the overall system architecture as a hierarchy of sub-systems and components
- mapping system components to 3D model components
- defining the numbers of active ovens relative to the total number of oven
- defining various oven profiles

- defining various parts types
- defining the mapping between part types and profile selection
- defining the oven selection strategy (cf. WP4-D12 report)
- defining the state sequences and the interlocks associated with states transitions

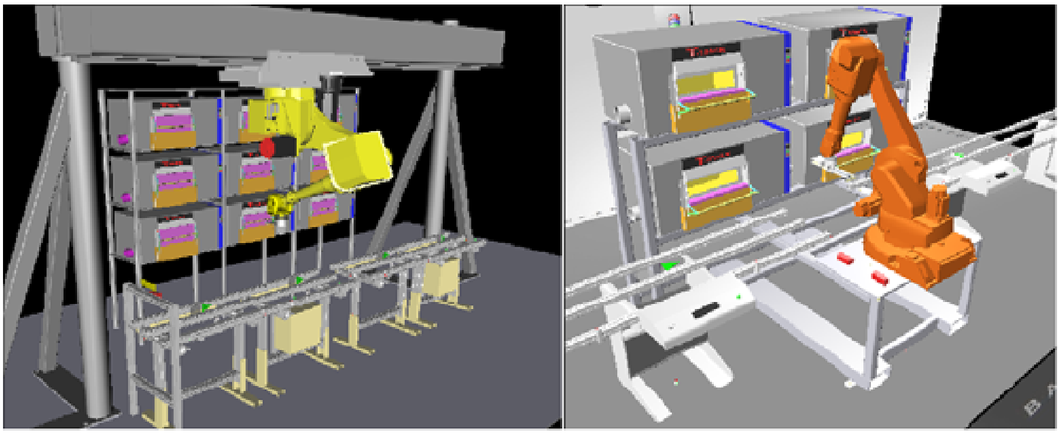


Figure 8: Examples of cell hardware configurations

2.4.2.2 Multi-oven system stimulation

The system simulation phase is executed according to (i) the parts types/oven profiles mapping settings, (ii) the oven profile settings and (iii) the states transition/conditions settings. The simulation phase outputs are (i) a log of all events occurring during the simulation and (ii) the animation of the 3D model. The GUI controls associated with the simulation phase are located in the part 2 of the SCS GUI. The GUI controls are divided in two tabs which are the “Timer” and “Panel” controls. The functions associated with those controls are:

Timer Related Controls - allows the user to start or stop a simulation run via buttons panel shown in Figure 9. When the timer is set to “Start”, all system parameters will be evaluated and events will be generated according to the system's internal control logic and external events (including part arrival detailed in the next section).

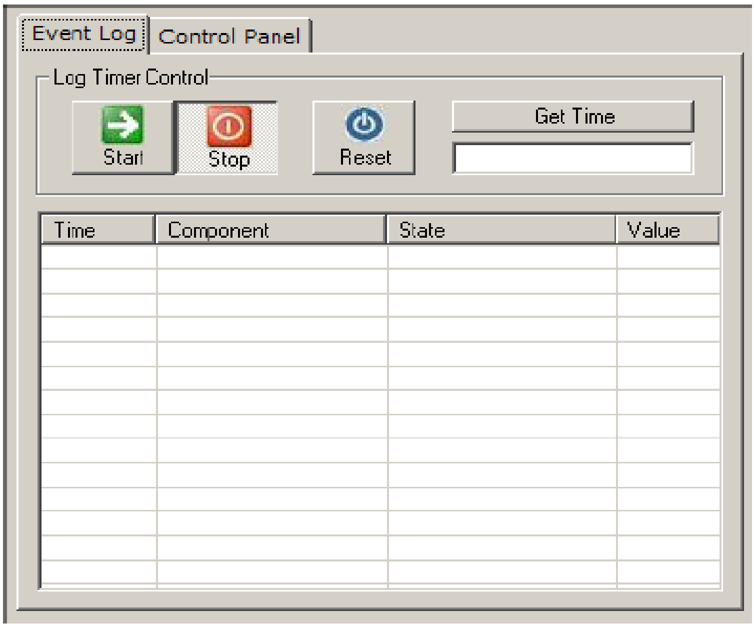
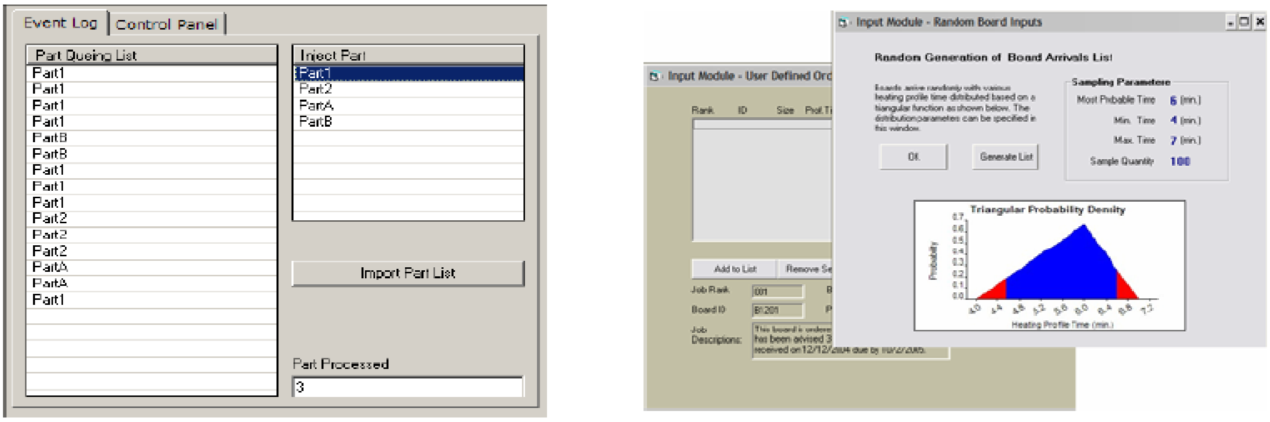


Figure 9: Time related control

Part Arrival Event Related Controls - allows defining the profile of part arrival during a simulation run. At this time, part arrival events can (i) be emulated manually by double clicking on the “inject part” list, or (ii) by importing a part arrival profile defined using PIP Modules, Figure 10. Each part inject into the simulation run will either be processed according to the cell configuration setting (i.e. Loaded into an oven, processed, unloaded) or queued (e.g. no oven available). Part will be removed from the queue when processed. The number of part processed by the system can be viewed in the “Part Processed” area.



Part Queing List
Part1
Part1
Part1
Part1
PartB
PartB
Part1
Part1
Part1
Part2
Part2
Part2
PartA
PartA
Part1

Inject Part
Part1
Part2
PartA
PartB

Part Processed: 3

Job Rank: 001
Board ID: B1201
Job Descriptions: This board is ordere… has been advised 3… received on 12/12/2004 due by 10/2/2005.

Random Generation of Board Arrivals List

Boards arrive randomly with various heating profile time distributed based on a triangular function as shown below. The distribution parameters can be specified in this window.

Sampling Parameters
Most Probable Time: 6 (min.)
Min. Time: 4 (min.)
Max. Time: 7 (min.)
Sample Quantity: 100

Figure 10: Part Arrival Emulation and User Defined Part Arrival List Generator

2.4.3 D12: Oven selection module for system integration

The Oven Selection Strategy (OSS) module provides the functionality required to achieve the oven selection priorities in order to process a part. The input parameters to the OSS module are as follows:

- A part arrival event as emulated using the “Control Panel” module of the SCS GUI
- The types of part to be processed as defined in the “Part Types” module of the SCS GUI
- The list of available ovens in the oven array as defined in the “Oven Set” module of the SCS GUI
- The oven profiles list as defined in the “Oven Profiles” module of the SCS GUI and the various parameters specific to each oven profile
- The part types / oven profiles mapping information as defined in the “Oven Profile Map” field of the part type parameters accessible via the “Part Types” module of the SCS GUI
- Information about the current state of system components identified as ovens
- The oven selection priority parameters defined using the OSS module and associated SCS GUI described in this document.

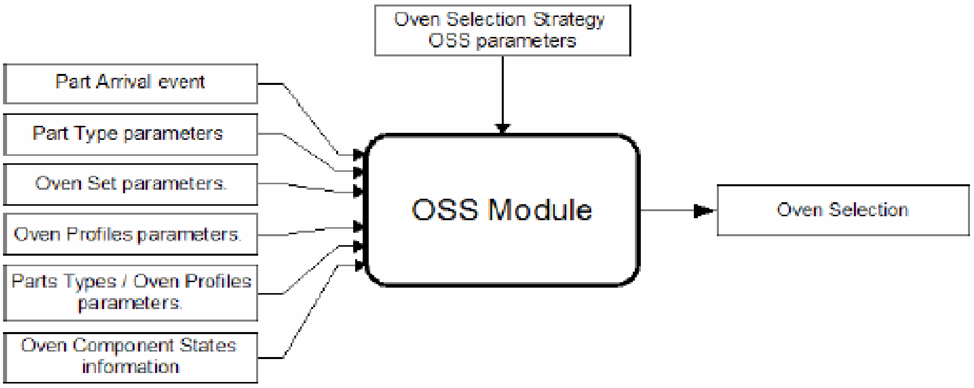


Figure 11: Oven selection module

2.4.4 D13: Statistical Process Control (SPC) Module

The SPC Module provides the functionality required to achieve the monitoring and processing of raw process data in order to provide system specific process analysis and management functionalities (e.g. number of boards processed, uptime, downtime, material usage, etc.). In addition to the process analysis tools implemented upon the Arena simulation engine/model, low level process analysis functionality has been integrated as part of the System Integration Tool Kit (SIT) that provides the integration infrastructure and Graphic User Interface (GUI) for the Supervisory Control System (SCS) and linked to the 3D based Virtual Prototyping Environment.

The SPC module functions are implemented based on (i) the states of components that compose the real and virtual system, and (ii) on the events generated by the modules that compose the SCS system (e.g. Oven Selection Strategy, Part Input Profile, Task Control, Virtual Reality Modules. The Illustration shows an example of results that can be obtained using the SPC GUI after running a simulation of a test cell composed of one robot arm and 4 ovens.

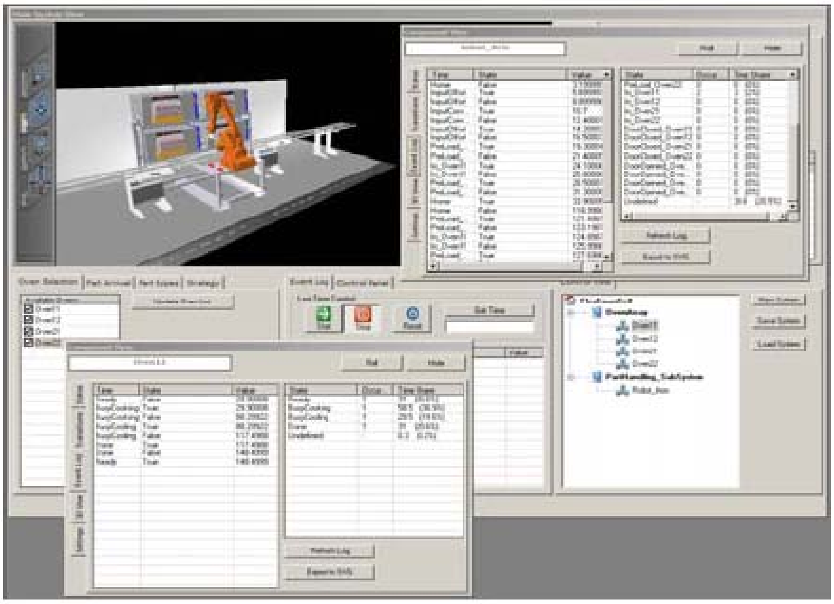


Figure12: Example of the stimulation run log, using the SPC GUI

The Event Log tab of each component detailed view presents to the user a list containing the state Id, state value and time for all the state changes for the component. This raw data is processed to extract:

- the number of occurrences for each of the component's states
- the cumulated time the component was in each state
- the percentage of the total simulation time the former time represents

The logged data can then be exported to Timing Diagram which allows a user to view all state change on the absolute time line provided by the Timer module, and to retrace the event history for each component that compose a system.

2.5 WP5: System Automation

This work package addresses the implementation and test of a transfer mechanism from the input and output conveyors as well as part recognition. A PCB carrier was designed which is transferable by the robot to and from the conveyor as well as directly being placed into the PRSC oven. The PCB handling system that is the robot is capable of transferring PCBs from a pickup point and distributing them to ovens selected by the supervisory control system and then removing them from the oven and delivering to an exit point. Deliverables 14 and 15 show a detailed account of the processes involved in programming the robot and the process of the automation system.

2.6 WP6: PRSC Engineering

This work package involved modifying the PRSC oven (T-Track) so as multiple units can be integrated into an automated system. The oven cavity was also modified to as the PCB carrier that the robot would use to transport PCBs to and from the oven is implemented with ease. A retro fit door and PCB carrier were designed to meet the requirements imposed by the automation system. Figure 13 shows the door retro fitted to the T-Track oven. The modified oven was tested by Seremap to ensure that the PCB handling system (robot) can manipulate the door design. The modified design also included open and close door switches which were inputed into the firm-ware of the PRSC oven. The PRSC communication protocol outlined in deliverable 16 was necessary for the central supervisory control system. Deliverable 17 outlines the retro-fit door mechanism.

Figure 13: Retro-fit door

2.7 WP7: PRSC Process Optimisation

Workpackage 7 is concerned with deriving a detailed understanding of the process physics, process-product interactions and process–materials interactions and thereby optimising the PRSC oven for a variety of production scenarios. A model of the PRSC is constructed to allow the exploration of process setups and configurations with their impacts on product processing.

Deliverable 18 reported the results of experiments carried out to study the effects of process parameters on solder product integrity and long term reliability. A thermal process model was also developed allowing investigations into process/product interactions.

Deliverable 19 presented a 'cookbook' which was derived to enable first time process set up of a product and to facilitate cell scheduling. The 'cookbook' provides guidelines in process setup for a variety of product types. The cook-book also deals with lead-free processing issues, such as: process profiles; inert gas consumption; process uniformity and accuracy of the thermal profiling and the effects of rapid cooling on the products and micro structures.

2.7.1 D18: Process Optimisation

Work package 7 was planned to provide a detailed understanding of the process of the lead-free soldering physics, process-product interactions and process–materials interactions and to optimise the PRSC oven for a variety of production scenarios.

The main criteria for optimisation of lead-free soldering using T-Track ovens were studied and experimented, and a thermal process model was developed to assess the impact of the innovative reflow approach implemented for the T-Track oven.

D18 contains the descriptions of the experimental tests carried out on the T-Track oven to evaluate the soldering parameters, which may be influenced by lead-free processes. In addition, the developed thermal model of the oven is documented.

2.7.1.1 Lead free soldering

Growing environmental awareness has led to increased legislation that restricts the use of toxic substances, and as a result from July 2006, new electrical and electronic equipment must not contain lead. Lead is widely used as a constituent of solders. Sn-Pb is the most common solder type due to its low melting range, and low cost. There are a number of possible alternatives to Sn-Pb solder. Extensive tests have shown Sn-Ag-Cu to be the best alternative solder. However, these solders have higher melting temperatures and for this reason, manufacturers are concerned about the compatibility of printed circuit board materials with lead-free solders. Furthermore, a lead-free solder will result in a different microstructure compared to leaded solders and the formation of these microstructures is not yet fully understood. The microstructure of the Sn-Ag-Cu/Cu assembly contains a number of intermetallic phases within a Sn-matrix. The size, distribution and morphology of these phases can affect the solder's strength and reliability. The reflow profile is found to be the main factor that influences the formation and characteristics of the intermetallic phases.

2.7.1.2 Experimental trials

The important issues in a reflow profile were identified as peak temperature, time at peak, cooling rate and reflow atmosphere. Additionally, PCB service conditions (e.g. very low temperatures or chemical atmosphere) may have different impacts on the lead-free solders in comparison with leaded solders.

A series of soldering experiments were carried out using a T-Track oven to investigate the effects of reflow parameters and subsequent service conditions on the microstructure of a Sn-3.8Ag-0.7Cu/Cu assembly. The trials focused on varying peak temperature, time at peak temperature, cooling rates and ageing environments.

A standard FR-4 board with 35 µm Cu finish was used as the test vehicle. The copper was etched to leave 6 copper pads of 2.5mm diameter. The boards were baked to remove any moisture and cleaned using iso-propanol. A type3 Sn-3.8Ag-0.7Cu solder paste was used for the experiment. A 0.7mm thick brass stencil was used to print the solder paste on to the pads.

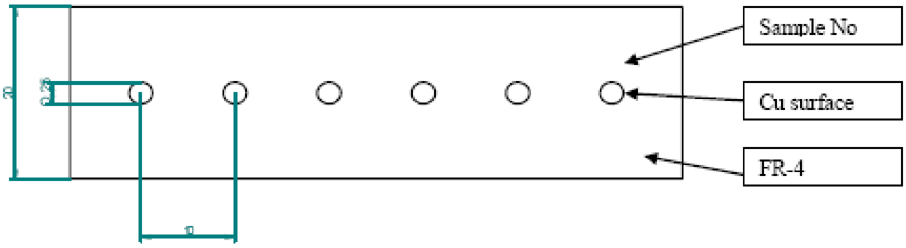


Figure 14: Test vehicle

After reflow a number of solder bumps were sectioned, mounted and polished to give the ‘as reflowed’ condition of the solder microstructure. Remaining samples were aged for 10, 30 and 45 days as prescribed by the experiment. These were also sectioned, mounted and polished for analysis.

Reflow - A traditional ramp-soak-spike profile was used pre-heating to 175ºC at 90ºC/min and soak time of 2 minutes to 190°C. A 40ºC/ min ramp was used to a peak temperature prescribed by the experiment. The time at peak and cooling rate also prescribed by the experiment.

Reflow Time - It is common for a device to endure several reflows. It has been shown that the IMC layer thickness increases with reflow time.

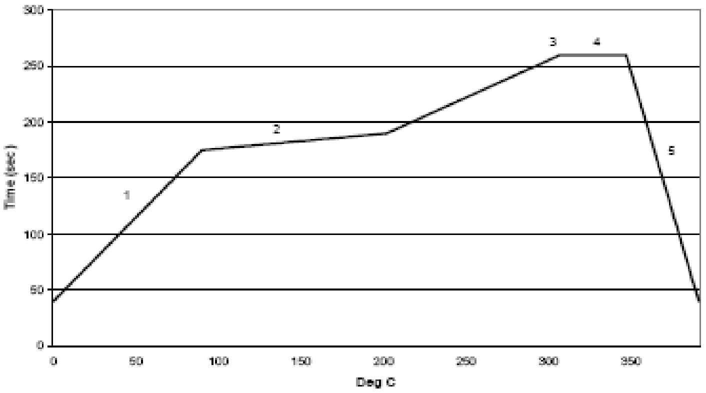


Figure 15: Ramp-Soak-Spike profile

Cooling Rate - The cooling rate has a significant effect on morphology of IMC layer. Generally a faster cooling rate will give a finer dendritic structure which has been shown to increase the strength of solder. Four cooling methods were selected to give a spread of cooling rates ranging from 0.3 ºC/s to 97ºC/s.

Reflow Atmosphere – As confirmed by other recent studies, the experiment also showed that wetting is improved in an inert atmosphere compared to air. However, it was also noticed in this study that reflow in a nitrogen atmosphere can increase the thickness of the IMC layer.

Ageing Process - During the PCB service life cycle the solder will be subjected to a range of temperatures. It is generally accepted that the IMC layer will grow when the solder is isothermally aged. To recreate the effects of service conditions, the reflowed samples were artificially aged or thermally cycled using the regime shown.

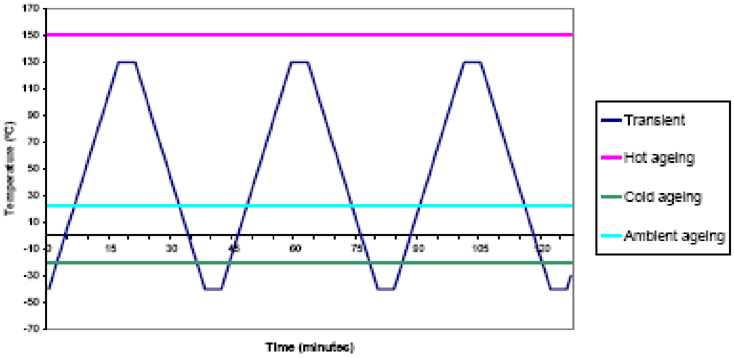


Figure 16: Ageing Regime

2.7.1.3 Experimental results

Once polished the samples were observed using a microscope. Images of each solder bump and their interface were captured. The following features were measured from images of the solder bump with examples in Figure 17.

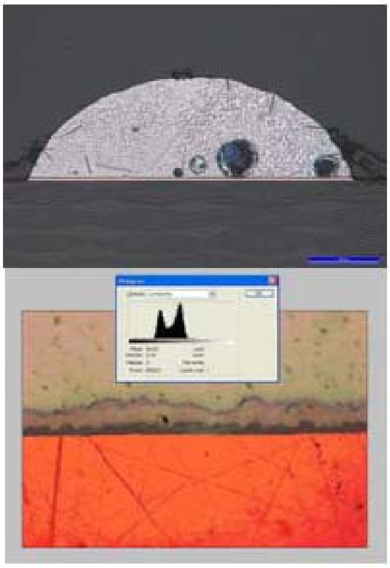


Figure 17

Ag3Sn plate - average size, distribution and angle from horizontal

Void - number, average size and distribution

IMC layer - average thickness and irregularity

The main conclusions from the study are summarised below:

- Cooling rate is the most influential factor to IMC layer thickness, closely followed by peak temperature and reflow time. The cooling rate is also the most influential factor to IMC layer irregularity.
- Ageing at 150ºC causes the greatest growth of IMC layer. Thermal cycling also causes growth of the IMC layer, but at a lower rate. Ageing in ambient and at -20ºC resulted in no growth of the IMC layer.
- Cooling rate is the most influential factor in the number of Ag_3Sn plate-type

phases, higher cooling rate resulting in a lower number. Cooling rate is also the most influential factor in the size of these phases, followed by reflow time and peak temperature. A lower cooling rate, and a higher peak temperature and reflow time results in larger Ag_3Sn plates.

- Peak temperature is the most influential factor to the presence of voids, where a lower temperature leads to a higher number. Lower peak temperature also causes the voids to be distributed much higher in the solder bump. The factors of the reflow profile are not responsible for the size of voids in the solder bump.
- For optimum soldering and reliability of Sn-3.8Ag-0.7Cu/Cu assembly, a peak temperature of 245ºC, a 10sec reflow time and a high cooling rate is recommended.

2.7.1.4 Thermal Process Modelling

This part of work package 7 involves the construction of a thermal/flow model of the PRSC process which will enable the exploration of process setups and configurations with their impacts on product processing.

2.7.1.4.1 The Model

Computational Fluid Dynamics (CFD) is used to simulate the air flow and temperature and the interaction between the heated fluid and the circuit board within the soldering oven. Due to the transient nature of the process for both air flow and temperature, transient CFD analysis was required to predict the heating of the product throughout the profile.

3D models of the different parts of the unit were constructed within the I-DEAS Master Modeller. I-DEAS modelling procedures were then used to define the flow path through the unit, which was subsequently meshed using tetrahedral solid elements. The CFD model takes into account all the internal geometry of the T-Track oven, including fans, heaters and duct openings etc. as illustrated.

The flow model is defined by specifying the flow properties of the fans which are custom designed cross-flow impellors. The two impellers are cycled in anti-phase between approximately 3500 rpm and 1750 rpm with a period of ~3s so when one motor reaches its maximum speed the other is at its minimum. This results in a moving wave of air across the PCB. The fans blow air through 6kW heater modules causing the air temperature rise. Figure 18 illustrate the two extreme phases of the flow oscillations. The interested reader should refer to Flex-Eman Website for animations of the flow and thermal models.

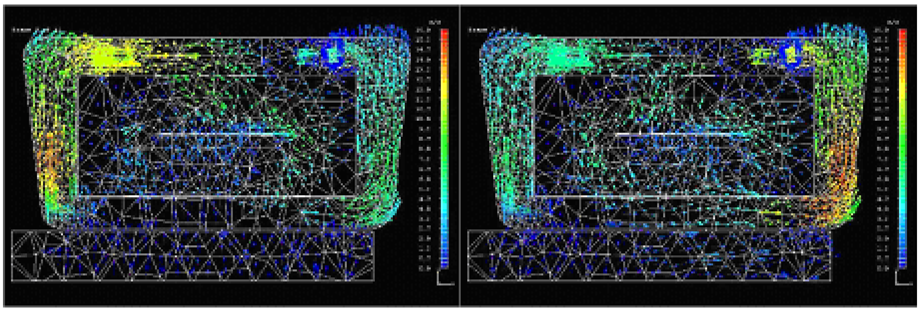


Figure 18: Flow pattern within PRSC

2.7.2 D19 & D20: Process operational profiles 'cook book'

The “cook-book” focused mainly on the processing of lead-free solder products. Processing of lead solders was also included for comparison and for those who may wish to use the PRSC oven for lead-based products.

A comprehensive set of experiments were carried out at Chalmers and Loughborough

Universities from which guidelines were drawn giving the near optimum conditions that should result in a defect free product that is not only mechanically strong but should prove reliable in the long term.

Chalmers University in collaboration with FOAB Elektronic AB studied oven profiling, board cleanliness, solder wetting, solder joint strength and void content.

Investigations at Loughborough looked at the effect of reflow variables and the subsequent ageing on the microstructure of a water-soluble SAC solder. The effects of peak temperature, time at peak and cooling rates, were studied on void content and intermetallic growth for a number of storage and thermal cycling schemes.

Based on experimental results, Chalmers and Loughborough produced a set of recommendations in the form of a cookbook to help an engineer with the first time profiling decisions of the PRSC oven to achieve cleaner boards with strong solder joints with thin IMC, fine microstructure and low void content. A summary of these findings is given here with the detailed account in document D19/20.

2.7.2.1 Temperature profile

For both lead containing and lead-free solders, the input temperatures in the T-track oven have to be higher than those recommended by the paste manufacturers, and higher compared to a conventional oven. A few experiments should be carried out to determine the desired profile for the particular assembly. The ramp-to-spike profiles given in the table are suggested as a starting point for solders tested. These are Sn-36Pb-2Ag with liquidus temperature of 189°C with a recommended peak temperature of 215°C, and lead-free Sn-3Ag-0.5Cu solder paste with reflow temperature of 217°C and a recommended peak temperature of 240°C.

Liquid nitrogen is essential for controlling the cooling rate of the product as well as reducing the cool-down time of the oven between runs to increase the board manufacturing throughput during production.

Sn-36Pb-2Ag		**Sn-3Ag-0.5Cu**	
Ramp Rate (°C/min)	**End Temp. (°C)**	**Ramp Rate (°C/min)**	**End Temp. (°C)**
50	235	50	275
-10	150	-12	150
-24	25	-24	30

2.7.2.2 Board Cleanliness

Air vs. nitrogen

- For best cleanliness, reflow should be carried out in inert atmosphere.
- When using lead-free solder pastes, reflow in nitrogen results in flux residues that are easier to clean compared to products reflowed in air.

Lead-free vs. lead-based solder paste

- Cleaner boards are achieved when using lead-free SAC solder pastes.

2.7.2.3 Solderablility

Air vs. nitrogen

- For best solderability results soldering in nitrogen atmosphere is recommended.

Lead-free vs. lead-based solder paste

- When soldering in air, the best solderability is achieved when using Sn-36Pb-2Ag solder paste

2.7.2.4 Wetting

Air vs. nitrogen

- The best wetting is achieved when reflowing in nitrogen atmosphere for both lead-containing Sn-36Pb-2Ag and lead-free SAC solder pastes.
- The wetting time is also reduced when reflowing in nitrogen atmosphere.

Lead-free vs. lead-based solder paste

- The wetting of the lead-free SAC solder alloy is in general poorer than the lead-based Sn-36Pb-2Ag counterpart.
- To achieve better wetting the use of a no-clean lead-free solder paste is proposed in preference to one with water soluble formulation.

Large pitch vs. small pitch components

- The best wetting is generally achieved for larger pitch components when compared to small pitch equivalents.

2.7.2.5 Solder joint strength

Air vs. nitrogen

- To achieve the strongest joints use nitrogen is recommended for both lead-based and lead-free solder pastes.

Lead-free vs. lead-based solder paste

- To achieve the strongest joints the use of lead-free solder paste is recommended. This applies to soldering in air and nitrogen atmospheres.
- For stronger solder joints the use of lead-free solder paste with no-clean flux formulation is recommended in preference to water-soluble variant.

2.7.2.6 Void Content in Solder Joints

In general to achieve the least number of voids, nitrogen should be used to inert the chamber during soldering[CU]. Using too low a peak temperature should also be avoided [LU] for a particular solder paste formulation. For example, common SAC solder alloys have a melting point of 217ºC-220ºC and solder alloy makers typically recommend a peak reflow temperature of between 12ºC and 43ºC above the melting point in order to achieve good wetting and to form a quality solder joint. It is found here that for such solders a peak temperature of at least 245ºC should be used.

Further recommendations for void minimisation are given below[CU]:

Air vs. nitrogen

- To achieve the least number of voids the use of nitrogen is recommended during reflow for both lead-free and lead containing solder pastes.
- To achieve less area occupied by voids again the use of nitrogen during reflow is necessary for both lead-free and lead containing solder pastes.

Lead-free vs. lead-based solder paste

- Lead-free is the preferred solder paste in order to achieve the least number of voids when soldering both in air and nitrogen.

- To achieve smaller area occupied by voids use Sn-36Pb-2Ag solder paste when soldering both in air and nitrogen.
- To achieve smaller voids use lead-free SAC solder paste.
- To achieve larger voids use Sn-36Pb-2Ag solder paste.
- For less number of voids no-clean solder paste is recommended.

Large pitch vs. small pitch components

- For both large and small pitch components, to achieve the least number of voids lead-free solder paste together with lead-free board finish is recommended.

2.7.2.7 Micro structures

On the whole, for a fine microstructure [CU] and a thin and regular IMC interface layer [LU] and thus a potentially stronger and more reliable solder joint, fastest cooling possible should be employed which can only be achieved using nitrogen. More detailed guidelines are given below:

- For a fine microstructure molten solder should be solidified as fast as possible.
- For SAC and Sn-Ag solders, to obtain spherical Ag_3Sn IMC, fastest cooling rate possible should be used. Furthermore, to obtain a rod like morphology of the Ag_3Sn IMC use a lower cooling rate (0.08°C /s).
- For thinnest IMC layer highest cooling rate, lowest peak temperature and lowest reflow times possible should be used while ensuring that the required wetting time is achieved. For Sn-3.8Ag-0.7Cu solder joint assembled on a copper pad, a peak temperature of 245ºC and reflow time of 10sec was experimentally found as a reasonable starting point.
- For a uniform and regular IMC layer, highest cooling rate possible is advised while ensuring that the required wetting time is also accomplished.
- For lower number and size of Ag_3Sn plate type phases highest cooling rate and lowest peak temperature possible is proposed.

2.8 WP8: PRSC Lead-free Soldering

The aim with W8 was to derive a detailed understanding of the optimum operating conditions of the Precision Reflow Soldering Chambers (PRSC) oven for lead-free soldering, in which the main deliverable was a “process operational profiles cookbook” to enable first time process set up of a lead-free product within the PRSC oven and to provide guidelines in process setup for a variety of product types. Chalmers University in collaboration with FOAB ElektroniK AB studied oven profiling, board cleanliness, solder wetting, solder joint strength and void content of the solder joint.

The “cook-book” focused mainly on the processing of lead-free solder products. Processing of traditional lead solders was also included for comparison and for those who may wish to utilise the PRSC oven for lead-based products.

A comprehensive set of experiments were carried out at Chalmers from which guidelines were drawn giving the near optimum conditions that should result in a defect free product that is not only mechanically strong but should prove reliable in the long term.

The milestone M9, which was the establishment of an EVOLVER surface tension model was not performed. The reason for this was that during the course of the work, Chalmers came to the conclusion that it would be more giving to analyse the formation and geometry of solder joints as a function of different process conditions, experimentally.

For that matter, the formation of the joints depending on reflow atmosphere (air versus nitrogen), solder paste composition (lead-free versus lead containing), board finish and component pitch (small versus large pitch) was analyzed by means of Optical Microscopy (OM). All of these results would be impossible to obtain through an EVOLVER model, which normally only takes into account the surface tensions of the different materials.

Chalmers believes, therefore, that the experimental analysis was of much more interest, importance and more rewarding to Planer compared to an EVOLVER model. The model would give possible shapes of solder joints depending on the solder's surface energy. The experimental analysis gives the real shapes and real depending not only on the material properties but also the different process parameters.

The study was based on OM pictures as shown in Fig. 19, where the solder joint shape and wetting characteristics on both the board and component lead side were analysed as a function of process parameters.

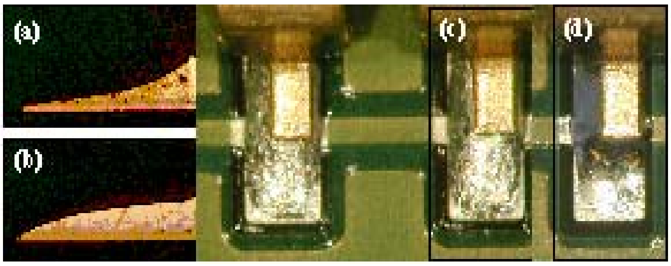


Figure 19 a) Cross-sectional view of SOP solder joint with Pb-containg solder alloy, b) Cross sectional view SOP joint with SAC solder alloy, c) Top view of joint depicted in (a), d) Top view of solder joint depicted in (b).

The deliverable D20, in the form of a Lead-free process profile cookbook for efficient utilization of the Flex-Eman PRSC ovens, comprising an analysis of impacts of rapid cooling on product integrity and in-process wetting properties of lead-free solders was delivered together with D19, which was the deliverable from WP7 having LU as leading contractor. D20 is also included in this report.

2.9 WP9: Application testing

The objective of WP9 was the construction of a demonstrator system consisting of a number of ovens and handling systems, including integration of the supervisory control system.

A prototype of a robotic flexible soldering cell was developed and tested in Seremap premises in France to investigate the applicability of the new soldering approach within the industrial environment. This prototype comprises of:

- a PRSC oven provided by Planner
- a robotic automation system capable of feeding 4 ovens, designed and built by Seremap
- a set of software applications to control the flexible soldering system developed by Loughborough University

These are detailed in project report deliverable 21. This document is divided into two parts. In part one the construction of the prototype (demonstrator) is described by Seremap. In part two, the development of the soldering cell control software is described by Loughborough University.

2.10 WP10: SME training

This work package was to provide and ensure that the SME partners have a full understanding of the underlying science and technology of the T-Track oven, agile automation and the lead free soldering technology. Realtime were responsible for producing training packages delivered via seminars, practical activities and any other means. However, it has not been possible for them to complete the relevant training resources. However, this is not regarded as problematic as, to fully understand the technology of the T-Track oven, a training day was held at Planer for the SMEs and together with the T-Track oven manual, it was seen that this was sufficient for the SMEs to full utilise the PRSC oven. The agile automation of the Flex-Eman cell is based on a simple and friendly graphical user interface. The Flex-Eman cell can be set-up and used with ease. Deliverable 22 has not been compiled.

2.11 WP11: Exploitation and Dissemination

The main objectives with W11 were to ensure the ultimate commercial and technical success of the project by detailed market research and identification and resolution of all apparent areas of risk, to disseminate the results in trade, through professional and academic press and to produce and exhibit a demonstration at an international trade fair.

Chalmers University in collaboration with FOAB ElektroniK AB carried out dissemination of results by publishing several conference articles and by presenting the results at different seminars, both national and international.

A public website has been launched with provides a project summary as well as information on all participants. Deliverable 24 provided suggestions on how to penetrate into the market as well as providing lists of manufactures that would be interested in the Flex-Eman system. Deliverable 25 lists potential drivers such as RoHS compliance that would lead end users to be attracted to the Flex-Eman system.