Intelligent Fault Correction and self Optimizing Manufacturing systems

Project Publishable Summary Report

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Coordinator	Odd Myklebust (NTNU)
Project website	www.ifacom.org

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1. Executive Summary

The vision of IFaCOM is to achieve a near zero defect level in all kinds of manufacturing, with emphasis on production of high value parts, on a large variety of custom design manufacturing and on high performance products. This shall be achieved through:

- Improved performance process control to reduce defect output and reduce the costs of defect avoidance
- Enhanced quality control to obtain more predictable product quality
- Enhanced manufacturing process capability independent of manufactured parts

The objectives of the project are to reach a level of excellence for a systematic body of knowledge on near zero defect manufacturing through improved process control, and long-range stability by use of intelligent manufacturing quality control systems.

In IFaCOM, this has been obtained through the development of new manufacturing strategies and methods which has been demonstrated in industrial cases. These methods have been designed in order to operate on three levels:

- closed loop control of vital parameters based on in-process real-time measurements
- medium time process tuning and optimization based on analysis of complex data sets
- optimized machine system for long-range performance improvement.

At all levels an intelligent sensing and signal analysis, supporting an intelligent fault diagnosis and prognosis system has been developed. This includes the development of a set of methods for real-time self-correcting mechanisms that give immediate effect and other methods for medium and long-range optimization that increase overall performance and stability. The application of the IFaCOM approach will have considerable impact on manufacturing processes, allowing manufacturing companies to obtain new levels of excellence and paving the road for the next-generation products, manufacturing, and services systems. The move will be towards zero-defect quality, using methods that encompass more than the traditional “six-sigma” methods based on standard defined data analysis. Manufacturing processes will be brought into higher stability both on short and long term by implementing process control strategies that avoid defects in real-time, continuously optimize process parameters based on analysis of multiple sensor data input from the process and improve the global process operational chain and maintenance strategy from today’s “Fail-to-Fail/Fly-to-Fix” to “Predict-to-Prevent” performance.

This improvements rely on the

- Development of system approaches for data monitoring of multidimensional fluctuation in product and process parameters for use in closed loop real-time control and medium to long-range optimization
- Development of process and manufacturing measurement methods and equipment, integrated in the machinery for real-time monitoring and control of vital parameters
- Application of advanced computational intelligence methods for analysis and decision making based on large complex data sets enabling product quality enhancement and predictability
- Creation of cognitive and self-adaptive devices that optimizes process parameters and machine system settings to establish high stability manufacturing systems with reduced manufacturing costs

The fulfilment of these sub topics of the objective will lead to better performance in industries that apply the new technologies developed and an opportunity for equipment manufacturers to offer new high performance products, machine tools and auxiliary equipment on the market.

Process measurements will be extended from the current few areas of application to a broad range of operations where there is a need to control vital parameters to obtain the required product quality without producing any faulty parts that have to be sorted out in the production process.

Today it is known that such challenges exist in the manufacturing of automotive parts, aerospace components, medical instruments, electronic products and other high performance products.

2. Summary description of project context and objectives

The concept of six-sigma was introduced by Motorola to improve the performance in high volume production of standardized products. It was based on the methods of statistical process control and has given substantial results in mass production, ensuring stable production with fault rates down to the order of 1-2 parts per million. This level of excellence can be transferred to other branches of industry that work with small/medium batches. Many of the companies belonging to this last category manufacture products that must meet extreme specifications. Defects in their products are simply not accepted. Therefore, the companies do put an extreme effort on checking, repairing or remaking parts to meet the specifications. For these companies the term "beyond six sigma" means improved methods and new process control methods that enables "make it right first time" manufacturing.

The basic philosophy is to reduce the variance much in the same way as in six sigma controlled volume production. The essential thing is to reduce all sources of variation, and to develop a method to eliminate the detrimental effects of unavoidable variance in material, part and processes quality that is the major source of defects in many manufacturing processes. To control this variance, it is necessary to identify its sources, developing methods that reduce the cost of eliminating the effects of this variance a posteriori. Figure 1 shows principally the main concept of such methods.

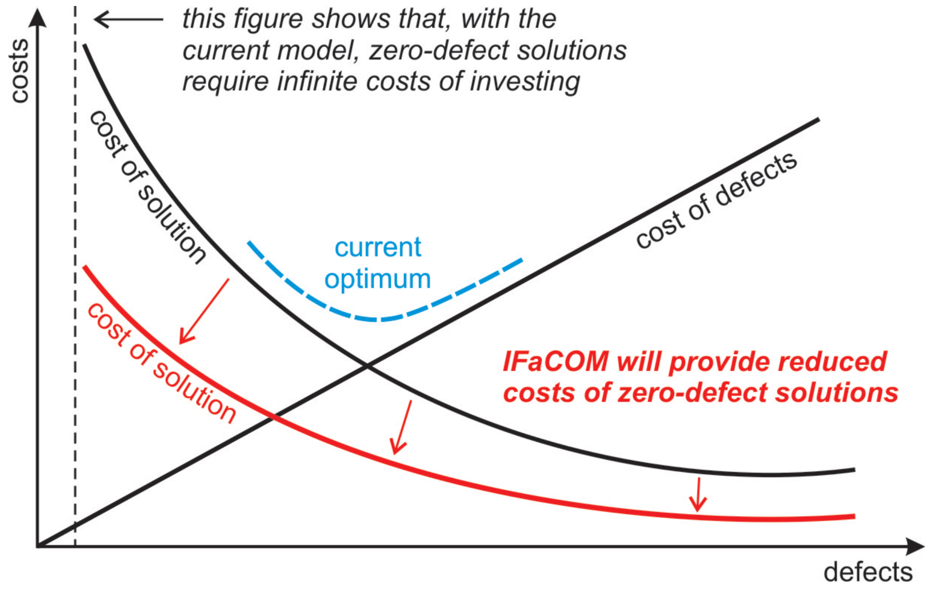


Figure 1: The cost effect of defects

A crucial aspect of developing and implementing effective diagnostic and prognostic technologies is the ability to anticipate/predict faults' onset in order to take actions that help preventing their occurrence. Fault isolation and diagnosis uses the detecting events as the part of the process for classifying the faults within the system being monitored. Condition and failure prognosis forecasts the remaining useful life and enables temporary stop of operations and resetting before proceeding. Within IFaCOM, methods such as Data Mining and Knowledge Discovery, and Evolutionary Optimization techniques have been investigated and their applicability in modern manufacturing environments evaluated.

As mentioned above, different process control strategies can be adopted, depending on the severity of the detected event and the time requirements of the corrective action.

In real-time control of vital parameters, the control loop must be fully automatic. In fact, only direct measurements of vital parameters and a quick data processing can ensure that proper reaction will take place in response to detection of an unwanted state within milliseconds.

For medium-term optimization, process simulation-based approaches have been developed to predict the process behaviour from the knowledge extracted from measured data. These approaches allow a continuous compensation of the allocation and distribution of part qualities across the entire process chain based upon the current measured status of the part-process-system qualities. This provides a global optimization of the entire process chain and can also be adapted to small lot sizes.

For long-range optimization of process parameters and maintenance, human judgment should be part of the loop to ensure that tacit knowledge about the process is included in the optimization loop. In IFaCOM, the use of modern computational intelligence methods has allowed to augment this knowledge through the analysis of complex data, ensuring that hidden patterns and trends are brought to the attention of the human operator. Figure 2 illustrates this concept.

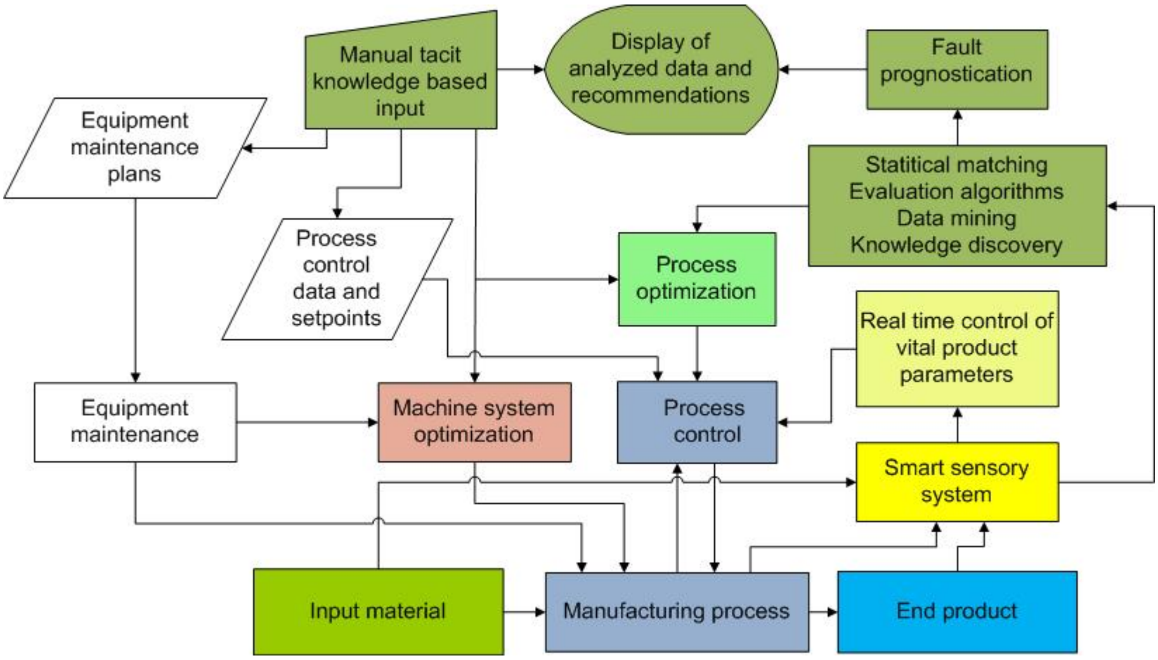


Figure 2: The IFaCOM Framework

Increasing the level of automation is considered to be the most viable approach to improve the competitiveness of manufacturing companies, especially those located in countries with high labour costs. In response to that, a number of automation solutions have been developed and successfully implemented over the years. Only a few of these, however, have achieved the ultimate goal of completely unattended manufacturing. In machining, operators are still monitoring the machines to observe abnormal sounds, vibrations or other indicators of abnormal operations. Furthermore, dimensions and other parameters are still checked manually after the process to perform fine tune operations and make corrections to program parameters to obtain optimal performance. This function of the operator relies on delicate human senses, such as vision, hearing and touch, and on the operator's abilities to make qualified judgments based on measurements and the information collected from these senses.

To mimic the behaviour of the operator a big number of sensor technologies have been developed and can be used for measuring a number of mechanical quantities like position, speed, acceleration, torque, strain, temperature, typically monitored in dynamic systems. Several devices for measuring these quantities are available commercially, and their operation has been amply described in textbooks and publications. Many of these sensor systems have been used in laboratory demonstrations of manufacturing process monitoring, while the intention of the IFaCOM project is to develop these methods and apply them in practical industrial implementations.

One common limitation of current monitoring techniques is the ability to provide useful information about the manufacturing process over the full range of operating conditions. The issue is that a particular sensor signal might be well correlated with a parameter of interest under one particular set of conditions, but would perform poorly once the setup is changed. A solution to this problem is the integration of signals from many different sensors, usually referred to as sensor fusion. This is usually combined with more complex analysis can give important information about the state of a manufacturing process. Such systems are usually referred to as intelligent sensor systems. Based on these considerations, IFaCOM has developed a system approach for data monitoring of multidimensional fluctuation in product and process parameters. Intelligent multi-sensor systems have been selected, developed in order to meet industrial requirements for durability and reliability, and the implemented and tested in the project's industrial cases.

The focus of the project has been also on methods to predict system developments toward unwanted states or faults, which is a crucial aspect for zero-defect manufacturing. An important part of developing and implementing effective diagnostic and prognostic technologies is based on the ability to detect faults in early enough stages in order to do something useful with the information. Fault isolation and diagnosis uses the detecting events as the part of the process for classifying the faults within the system being monitored. Condition and/or failure prognosis, then, forecasts how long the process will stay within tolerance limits.

Condition diagnosis is crucial in the whole system. Nowadays, statistic matching, data mining and knowledge discovery are tended to be implemented in condition diagnosis, with methods like Artificial Neural Network, Fuzzy Logic System, Genetic Algorithms, Hybrid CI (Computational Intelligence) Systems, etc.

Relying on these methodologies, during the IFaCOM project the consortium has developed a system approach for monitoring and processing of data's dimensional fluctuations, in which automated, flexible and intelligent simulation and prognosis system is used to predict the manufacturing system and processes behaviour. This approach has been applied and validated in industrial processes. Depending on the application case, new computational intelligence tools such as Data Mining and Knowledge Discovery have been applied while also some simulation tools and methods have been developed and can be used for efficient operation planning combined with in-process monitoring.

In IFaCOM, five industrial end users have participated; they have been selected to demonstrate important characteristics and benefits that can be obtained through the application of the IFaCOM methodology, both in the Machine Tools and Aerospace fields; they are listed in Table 1.

End User	Sector	Industrial scenario
GKN Aerospace Norway AS	Aerospace	Automatic positioning and offset correction of turbine vane segments for machining exhaust case struts and outer case segments for welding, and in process measurements and real-time control of tool wear and surface quality.
Europea Microfusioni Aerospaziali Spa	Aerospace	Reduction of the risk of defects in production of jet engines components by increasing the automation level of the process and adopting an improved control approach based on artificial intelligence.
Alesamonti Srl	Machine tools	Application of the outcome of the SOMMACT project to a wider area than the machine tool itself, i.e, the incoming part and its clamping, the identification of vital parameters and to optimization of the complete manufacturing process.
Strecon AS	Machine Tools	Automatic control of surface quality in automatic polishing of high performance injection molding tools.
Agie Charmilles New Technologies SA	Machine Tools	Addition of new sensors to EDM machines to obtain in-process information to get improved control of accuracy, precision and surface quality of produced parts.

Table 1: IFaCOM demonstrator cases

3. Description of the main R&D results/foregrounds

During the IFaCOM project different types of activities have been carried out.

a) RTD

b) Application and demonstration

c) Dissemination and exploitation

d) Management

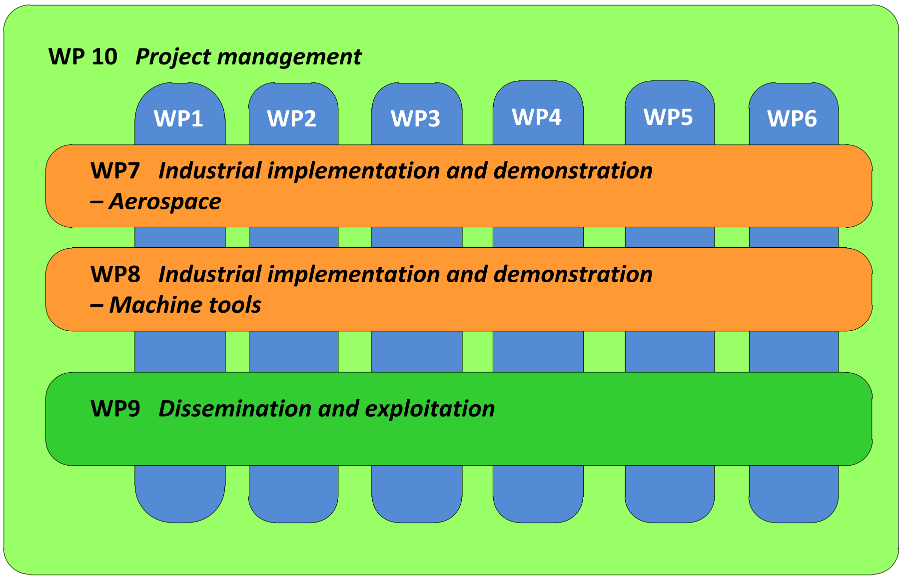


Figure 3: Structure of the IFaCOM Research, Application and Innovation activities

RTD has been the core focus of the project in the first period, while the second phase has been characterised by a synergic effort on two fronts, the last part of research studies and their implementation into the selected demonstrator cases. Other activities, like project management and dissemination and exploitation of project results have been constantly carried out during the project, as shown in Figure 3.

WP	Focus
WP1	Description of industrial needs from participating companies and handling overall IFaCOM system integration.
WP2	Characterization of functionality and capabilities of sensor systems for manufacturing equipment, part and process status analysis. Selection of sensors, sensor fusion and measurement systems for the project companies.
WP3	Methods for identification of vital parameters in representative manufacturing systems, and for validation of the parameters.
WP4	Methods for sensor signal processing, feature extraction, pattern recognition, cognitive algorithms, and making decisions for zero defect manufacturing.
WP5	Methods for in process control to obtain targeted values for the quality parameters.
WP6	Information system and method for optimization over time based on modelling and simulation. Methods for combination of these results with tacit knowledge of experienced operators to achieve long-time optimization.

Table 2: IFaCOM RTD work packages focus

The Research WPs have been planned as vertical activities to develop results to be applied and demonstrated in the different applications (aerospace and machine tools). Dissemination and exploitation are indicated as horizontal activities based on results from both research and applications. The IFaCOM RTD implementation plan included fundamental and applied research activities in the disciplines of manufacturing process monitoring and instrumentation, data validation, large data set analysis, real-time process control, process and machine system simulation and optimization. The focus of each RTD work package is described in the Table 2. The results of each of these WPs are described more in details below.

3.1 WP1

The main function of WP1 has been supervising the project RTD activities and conveying their results into the demonstrators.

The first activities were focused on creating a common understanding on processes and available technologies/methodologies for improving the production quality. Information from industrial partners have been collected via several questionnaires. Based on the data retrieved, the consortium has performed a detailed analysis of the end user processes and products, with a special focus on current technologies applied in production lines at the end users factories for reducing the scrap rate. Within this analysis, end users have stated their research priorities (user requirements) and critical steps in the targeted production processes have been identified, presenting several proposals for heading towards zero defect manufacturing. In addition, technology suppliers have presented their core technologies and their potential developments for solving the identified criticalities or for providing useful tools for the IFaCOM system.

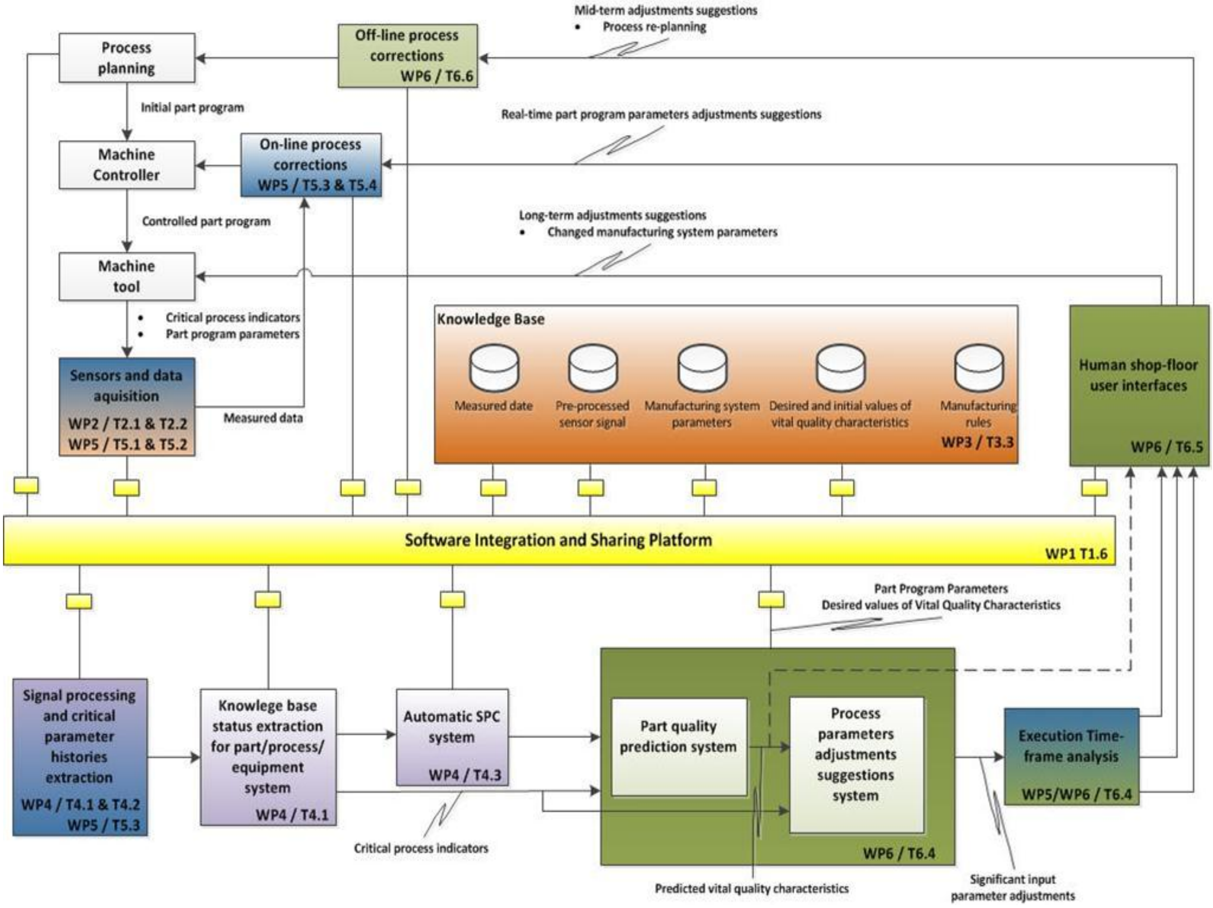


Figure 4: Proposed system architecture

Once consolidated the knowledge of processes and technologies, a methodology for the identification process vital parameters in each end users cases has been studied and applied, performing a detailed analysis of each step of the production chain with respect to incoming materials, fixturing and tooling, manufacturing system, production process and produced part.

On the basis of the collected specifications and the results of the performed analyses, the industrial IFaCOM functional framework model has been further analysed and adapted to each end user cases.

The framework provides basis for all research efforts of IFaCOM in order to achieve Zero Defect Manufacturing solutions in the different industrial cases. Also, a detailed analysis of the generic technologies to be developed within the project and their customization to the end user cases has been carried out; results have been formally represented by using IDEF0 functional models.
In this context, also the IFaCOM overall system architecture for the software and hardware application systems has been drafted and updated, with a clear specification of the development to be done in the different project WPs/tasks (see Figure 4).
A customized version of the architecture has been also designed for each end-user, defining the interfaces between the software modules and allowing the practical implementation of the IFaCOM concepts.
Based on these specifications, in the last phase WP1 has also taken care of system integration issues with a special attention paid to implementation issue, defining guidelines for the implementation of RTD results into the demonstrators and continuously updating and applying contingency plans whenever issues arose. Finally, WP1 has also organised all validation activities done in RTD WPs.

3.2 WP2

WP2 has focused on establishing sensor systems solutions and strategies for the real-time assessment of the status of the manufacturing system, the manufacturing process and the part during operation. This work started from the development of methods for the identification of part-process-system vital parameters realized in WP1 and encompassed the characterization of functionality and capabilities of sensor systems, selection of optimal sensor solutions, development and implementation of optimal hardware and software solutions for integration of sensor systems in machine tools and in aerospace processes. The capabilities of the developed sensors systems solutions have been demonstrated by implementing them into the project’s end user cases.

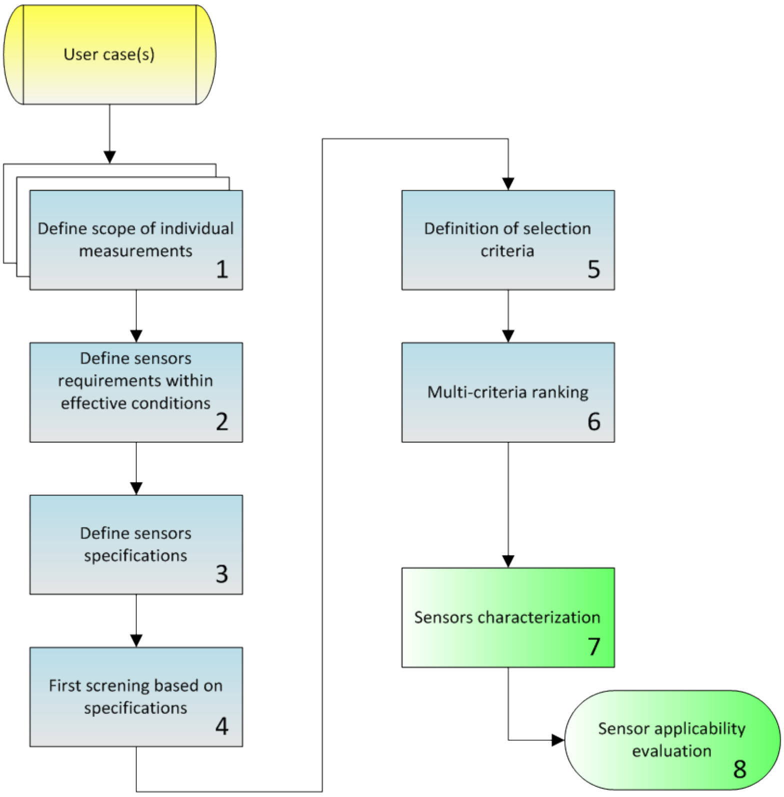


Figure 5: Sensors selection and characterization procedure

The first task of the WP has been the identification of measurement and sensor system solutions suitable for the monitoring of the identified relevant (vital) parameters. This work has been carried out on the basis of the characteristics of the signal to be acquired and on the sensitivity to the processing environment. Force, torque, displacement, deformation, dimension, temperature are among the quantities measured for active part-process-system control. The specific sensor technology strongly depends on the signal amplitude, frequency spectrum and noise level. The different applications targeted in the demonstrator WPs (WP7 and WP8) exhibited different requirements. State-of-the-art off-the-shelf sensors, as well as newly developed sensing solutions including sensor fusion, has been considered with respect to both direct measurement and indirect measurement of the relevant parameters. Sensor systems were characterized and evaluated with respect to several performance indicators (performance, cost, robustness, long-term reliability, suitability for integration on the manufacturing system in a production environment, etc.) according to the ad hoc procedure developed in WP2 (Figure 5).

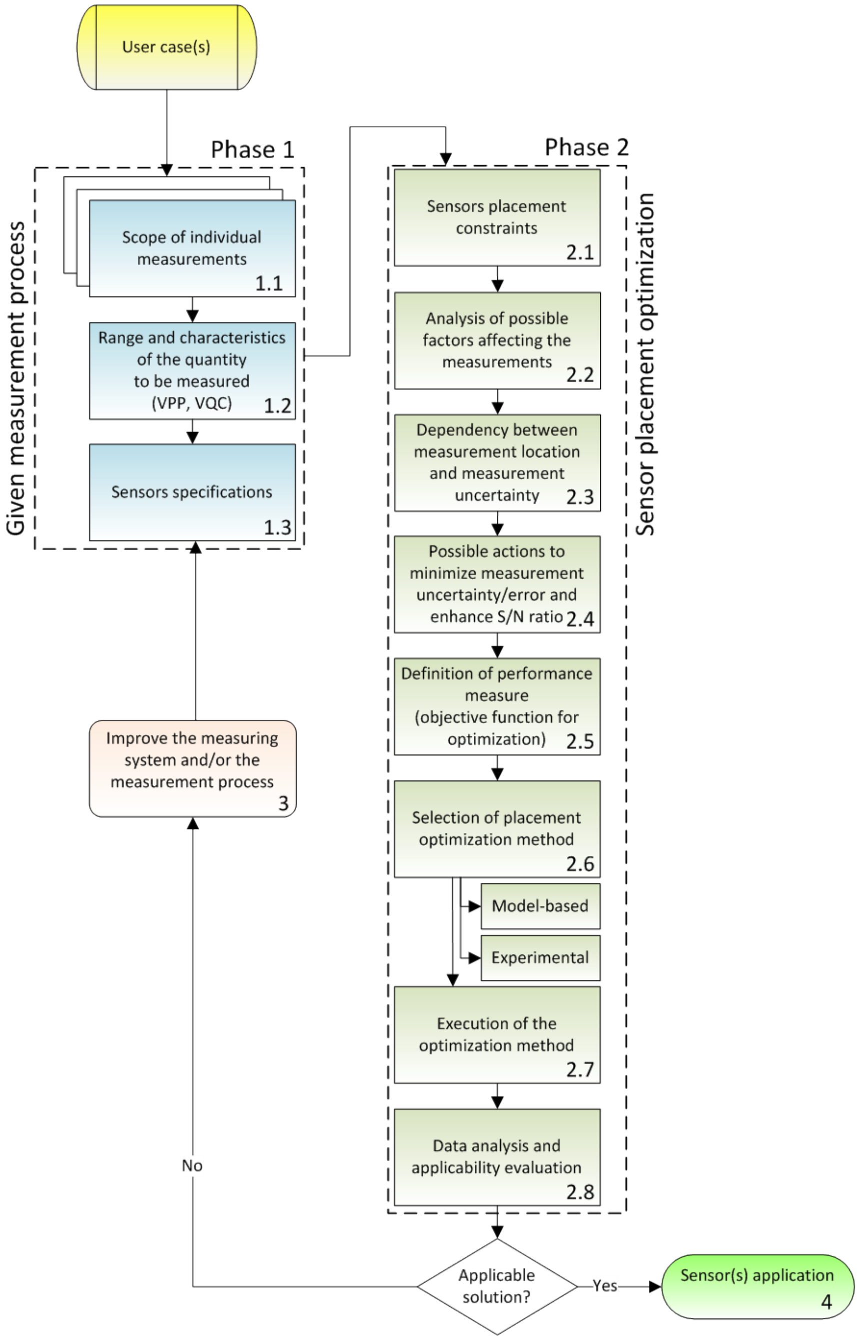


Figure 6: Method for identification of sensor system location

The following task in this WP has focused on the development of optimization methods for the identification of the most suitable locations of sensors in order to maximise the ratio between measured effect and sensitivity as well as the ratio between measured effect and signal noise. A systematic approach has been developed (see Figure 6) based on part-process-manufacturing system models as well as on experimental analysis and testing procedures.

Then, since the analog signal from the sensor usually cannot be connected directly to the A/D converter, pre-processing has been analysed in details (filtering, amplification, A/D conversion, segmentation) for the selected hardware/sensors.

3.3 WP3

This WP has developed new methods and systematic approaches for validation, structuring and storage of acquired data as a preparation for data processing.

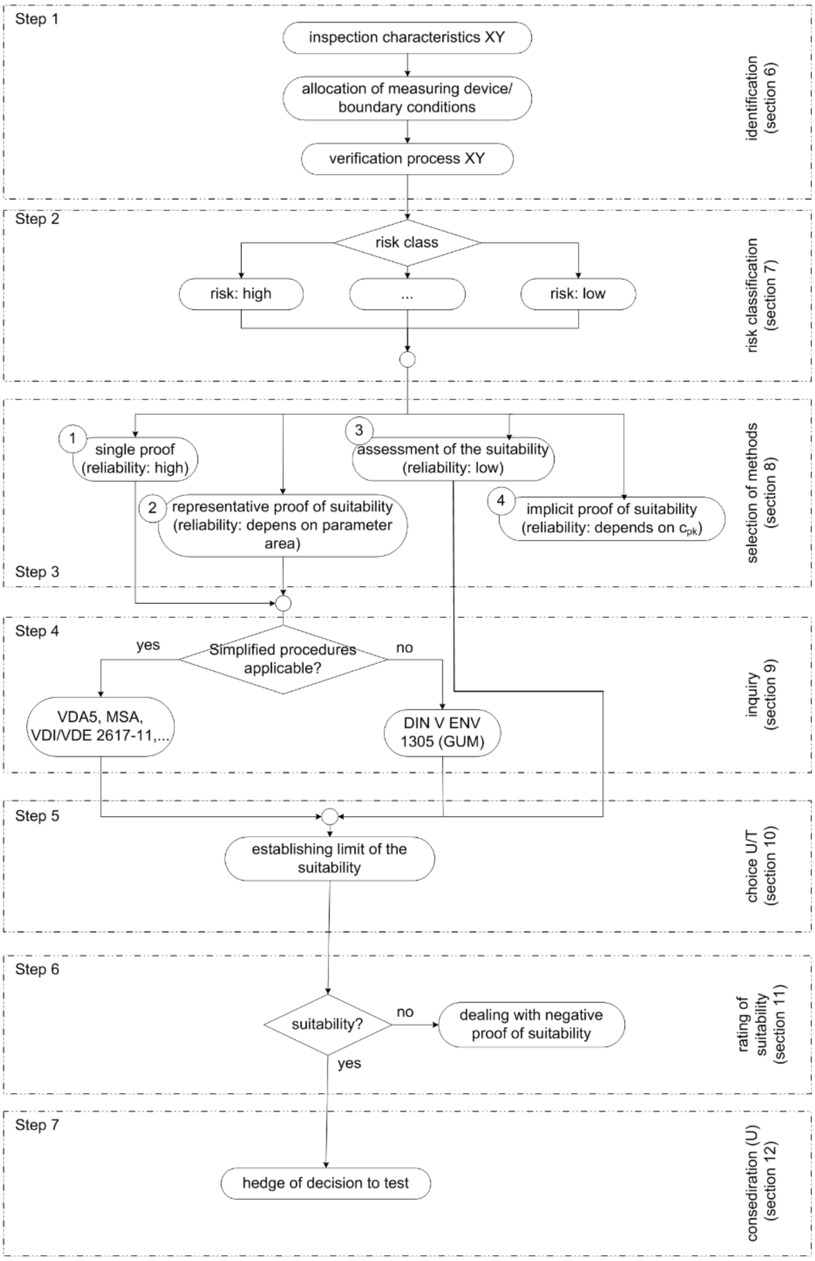


Figure 7: Overview of VDI/VDE 2600-1 methodology

As a result of a measurement, information about the product and production process is gained which can be used for production control. The information quality strongly depends on the measurement process which can be described by multiple parameters like the measurement uncertainty, the measurement point density etc. A very important parameter with respect to a zero defects quality level is the level of integration into the production process. While the results of in-line or in-process measurement systems can be used for quasi real-time production control, post-process measurements can only be used for a long-term process control. On the other hand, in-line or in-process measurements have to be performed within the production cycle and within production environment. In many cases, this leads to a higher measurement uncertainty. Today, there exists no systematic approach to design a measurement process with respect to all parameters which are relevant for production control. In many companies, measurement processes are designed only with respect to the specified feature tolerances. To achieve a near zero defects manufacturing level, it is therefore necessary to enhance the conventional approach to describe and design measurement processes with respect to their use for production control. An organizational structure has to be defined which supports an early consideration of measurement processes in the setup of manufacturing processes.

As mentioned above, the quality of information which is gained through measurements differs and depends on the measurement process. To use measurement data for production control, it is very important to validate the measurement results and to know their level of reliability. The validation includes the usability of the data for quality control and the evaluation of the measurement uncertainty. Methods for the uncertainty evaluation of a single measurement process are described in numerous standards and guidelines. Nevertheless, as there are many measurement processes in each company and the validation of measurement processes causes a lot of effort the existing standards or guidelines cannot be used economically, especially by SMEs.

To achieve a near zero defects manufacturing level, IFaCOM has developed a new validation methodology for measurement processes according to their relevance for production control. This methodology enables all companies to validate their measurement data economically. The core element of such an approach is the evaluation of the risk connected with a false decision based on a measurement and the influence of the measured parameter on the product quality. Measurements are classified into risk categories according to their relevance to the product quality and according to the probability of an erroneous measurement decision. Depending on the risk category, appropriate methods for efficient evaluation of measurement uncertainty and proof of capability are presented. This approach (see Figure 7) has been implemented into a German VDI/VDE guideline.

Always in WP3, the consortium has addressed the aspects of the preparation of all gathered measurement data and the data storage in on database in order to guarantee its efficient handling and maximize their use through the aggregation of information qualifying the measurement, especially for validation purposes (see Figure 8).

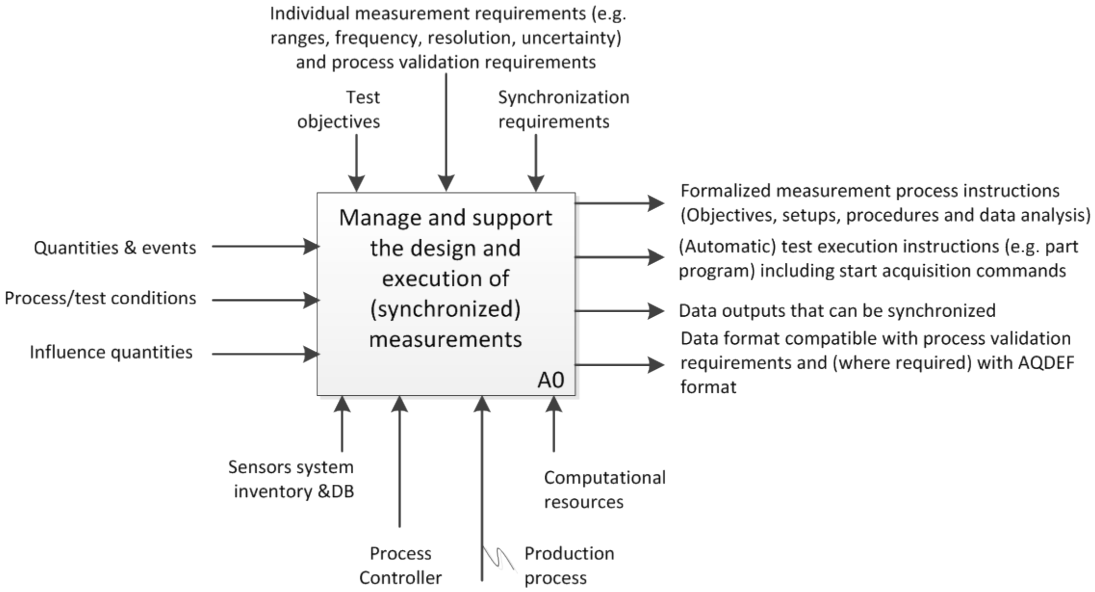


Figure 8: Functional description for measurement information aggregation

Sub-suppliers to the aerospace industry are required to validate not only their products but also the manufacturing processes, in order to comply with the international regulations and to achieve highest safety in operation. Although each single component critical for safety is thoroughly verified, still in many cases unpredicted failure occurs. Such failures have often dramatic consequences with high economic losses and in some cases losses of human lives as well.

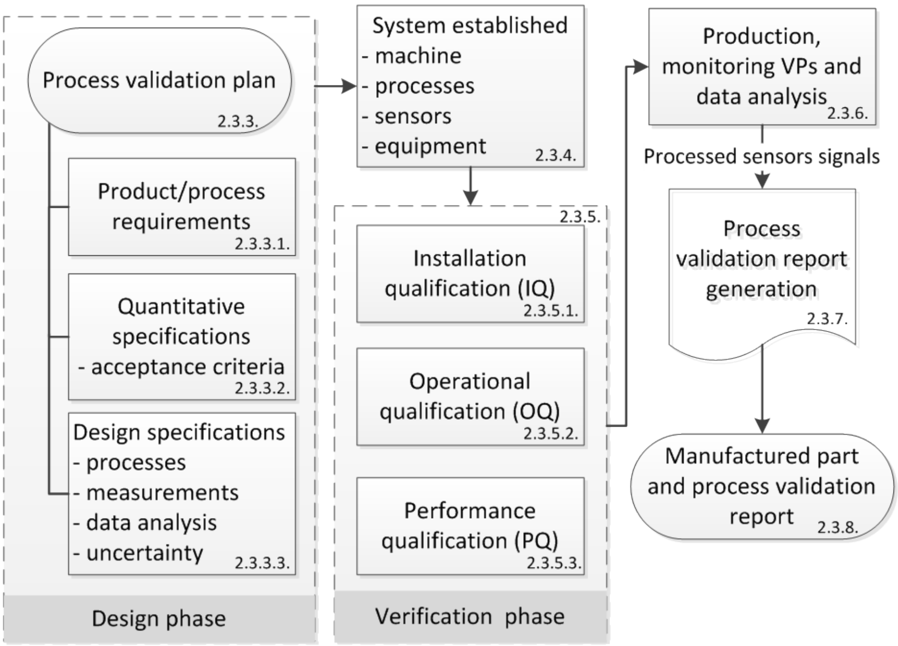


Figure 9: IFaCOM process validation framework

The concept of IFaCOM is based on the intelligent monitoring of vital parameters (VPs) in order to enable prediction of undesired processing conditions, suggestions for process corrections as well as real-time adaptive processing for a large range of manufacturing processes. This approach, besides virtually leading to zero defect manufacturing, provides also a documented evidence that for each process step of any process chain, each processed part will be within specifications. Then, thanks to the implemented sensors and monitoring systems, important information can be gathered for part, process and manufacturing system during operation, providing a detailed documentation of any event occurred during the process. Based on these considerations, IFaCOM has developed a procedure for process validation (see Figure 9).

3.4 WP4

This WP has coped with the processing of the sensor signals acquired by the sensors selected within WP2 and applied to the manufacturing processes selected in WP5 and WP6.

The first step in this direction has been sensor signal feature extraction, carried out in the time domain, in the frequency domain and in the time-frequency domain. Signal features must describe the signal adequately and maintain the relevant information about the process conditions.

For time domain feature extraction, several features have been extracted (arithmetic mean, average value, magnitude, root mean square, variance, standard deviation, skewness, kurtosis, signal power, peak to peak range or peak to valley amplitude, crest factor, signal ratios, etc.) and different time domain feature extraction techniques have been selected and used depending on the application requirements (statistical analysis, time series modelling, principal component analysis, etc.). For frequency domain feature extraction other techniques have been adopted (fast Fourier transform, discrete wavelet transform, wavelet packet transform, etc.).

For evaluating the correlation between the original signal and the features and selecting features which are really representative of the signal, different techniques have been used (Pearson correlation coefficient, Taguchi's orthogonal arrays, etc.).

When measuring a particular variable, a single sensory source for that variable may not be able to meet all the required performance specifications. A solution to this problem is sensor fusion that combines sensory data from disparate sources so that the resulting information is better than would be possible when these sources are used individually.

The sensor fusion approaches followed in the project are based on multiple sensor monitoring systems and direct fusion paradigms (i.e. fusion of sensor data from a set of heterogeneous or homogeneous sensors and history values of sensor data) and/or indirect fusion paradigms (i.e. sensor fusion that uses information sources like a priori knowledge about the environment and human input) selected as the most effective for the applications of interest for the project (see example in Figure 10).

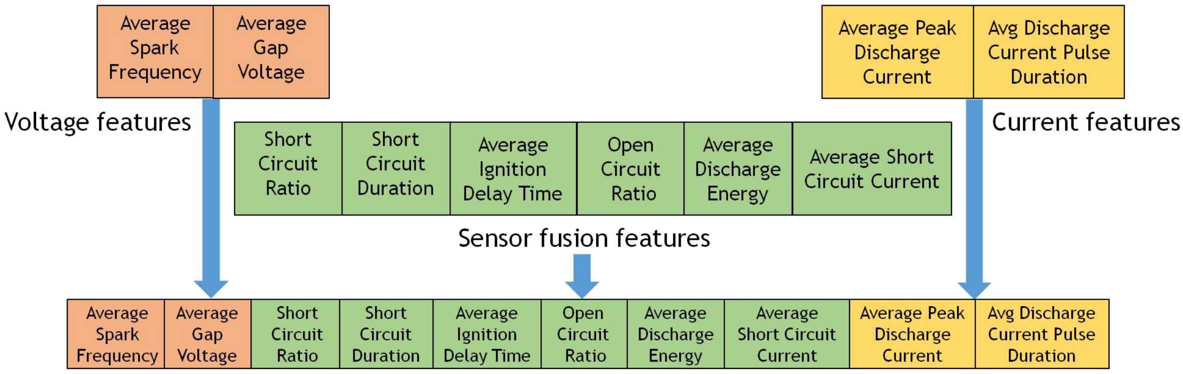


Figure 10: Example of sensor fusion pattern vector for the Agie Charmilles' case

After feature extraction and sensor fusion, several cognitive computing methods have been applied for implementing intelligent sensors and sensorial systems, which perform as decision making support systems functional to come to a conclusion on process conditions based on sensor signals data features. These include expert systems, artificial neural networks, fuzzy logic, neuro-fuzzy systems, genetic algorithms and hybrid systems able to combine the capabilities of the various cognitive methods. The most effective cognitive paradigms for the process monitoring applications of interest for the project have been selected, customised and implemented in different end user cases (see Figure 11).

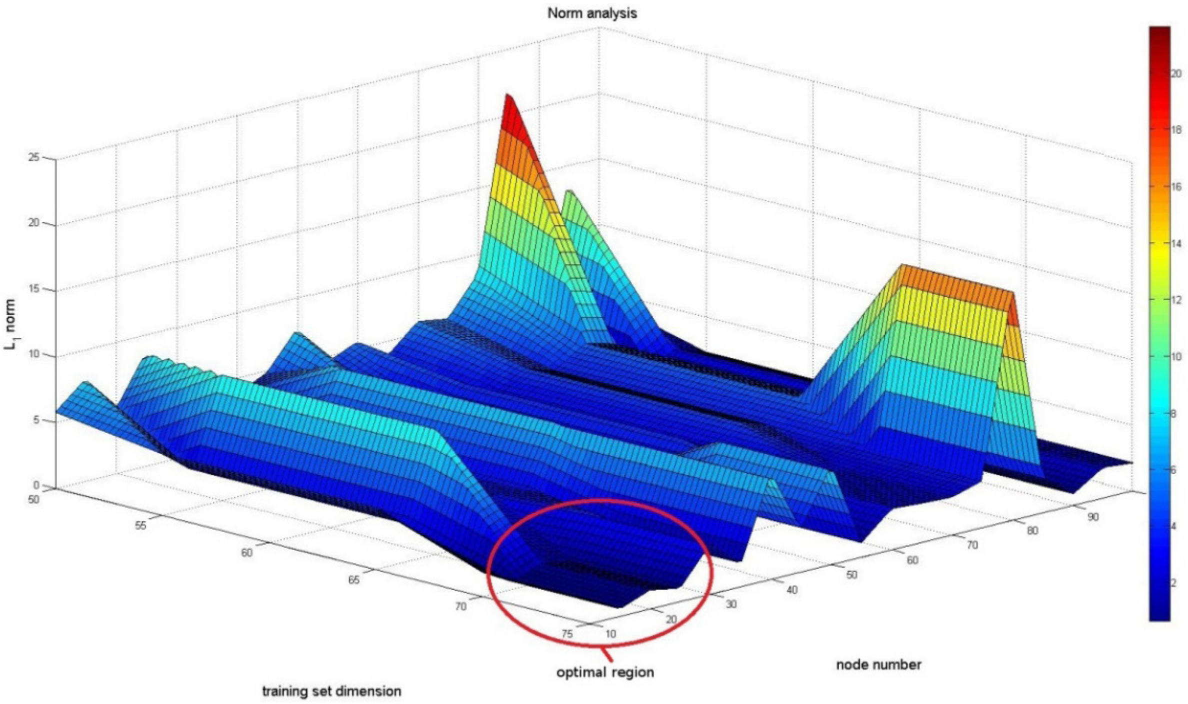


Figure 11: Optimization of the neural network setup for the EMA's case

3.5 WP5

Within IFaCOM each demonstrator implementation had different demands regarding the software , i.e. interfacing with various sensors, programming of custom signal processing functions for each sensor, etc. Therefore, it was not possible to develop a completely “plug & play” system. Instead, a framework was developed, and his functionalities were analysed using the data flow diagram shown in Figure 12.

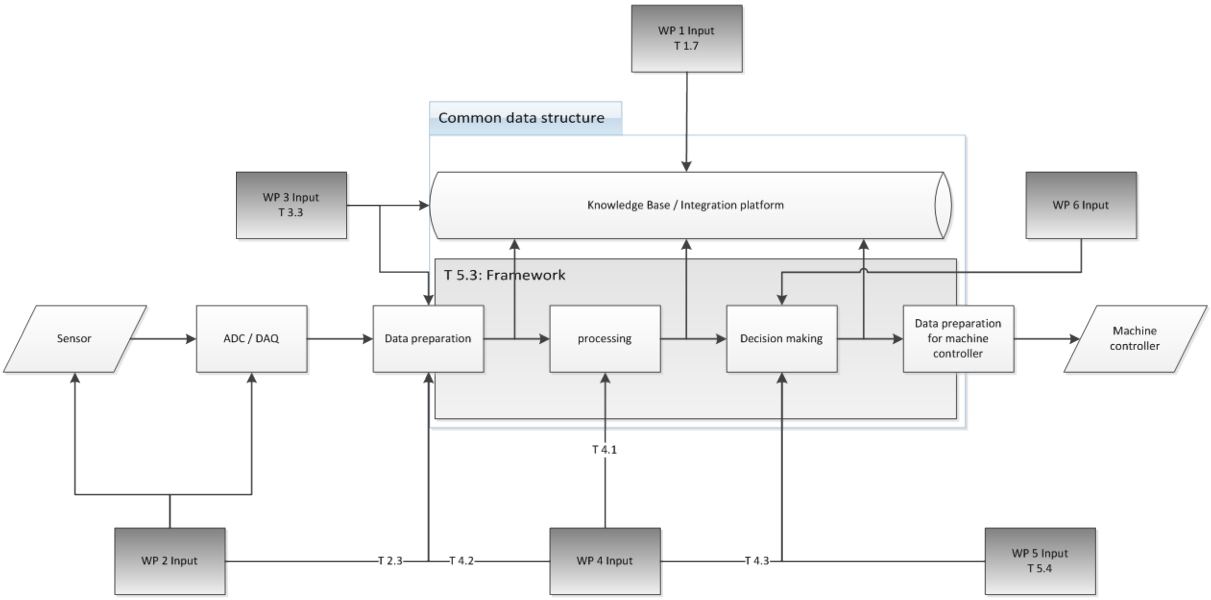


Figure 12: Data flow diagram of the IFaCOM-System

The framework chosen and developed within WP5 is identical for each demonstrator and manages to call the correct sequence of functions for the sensor data; it relies on a configuration file which adapts the software to the demonstrator by providing necessary preferences and matching sensor data with the (signal-) processing functions.

As seen in the data flow diagram, the system gets sensory data from a DAQ-System. The first step (data preparation) is to acquire this data and store it in the system in order to call the subsequent functions with this data. This can only be covered in generic software due to different hardware interfaces. For instance, some DAQ-Systems need specific drivers and therefore specific functions to establish a connection to the hardware and read the data. This applies particularly for sensors with their own DAQ-System. After the data is stored, the (signal-) processing functions are called. Depending on the information in the configuration file, the correct sequence of functions is called in order to extract the necessary features from the signal, which are correlated to the relevant process parameters. These features are also stored in a dedicated common data structure and are delivered, with additional information if necessary, to the decision making function.

The output of the decision making function includes a list of parameters with the corresponding adjustments. This information is sent to the machine controller. A common data structure within the software was defined in order to simplify the adjustments to the different demonstrators and to integrate new functions.

An important aspect coped with in WP5, is modularisation for guaranteeing greater system adaptability. If needed, the system modules should be able to run on different devices without losing functionality. To achieve this, a common communication protocol should be defined, and the software should comply with several requirements (efficient communication, secured data transmission, communication on local host, and optionally over the network (LAN) or Internet (WAN), support for interface development in different programming languages, easy set up, etc.).

Different open-source or private communication software were envisaged within WP5 and Apache ActiveMQ software (Figure 13) was selected as a basis for the communication for non real-time needs. It is an open source Message Oriented Middleware (MOM) for sending messages between two or more clients through a message broker, which provides standards based, message-oriented application integration across many languages and platforms.

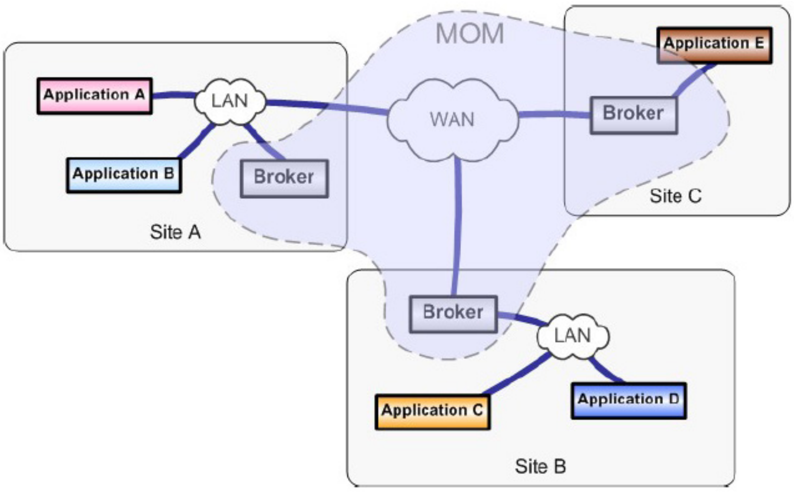


Figure 13: Principle of ActiveMQ communication

3.6 WP6

This work-package has defined, developed, implemented and validated a Simulation-based, Intelligent Fault Diagnosis and Prognosis System for Optimization over time (SIFDPS) so that the manufacturing of a part is achieved within its specified quality.

This system consists of the following three main sub-systems:

- A semantically enriched (with part quality definitions) part program system across the process chain (SEPM)

  According to the developed method, the definition of a desired multi-stage part program is upgraded with a formal description of the desired part qualities, defining a Semantically Enriched Process Model (SEPM, see Figure 14)

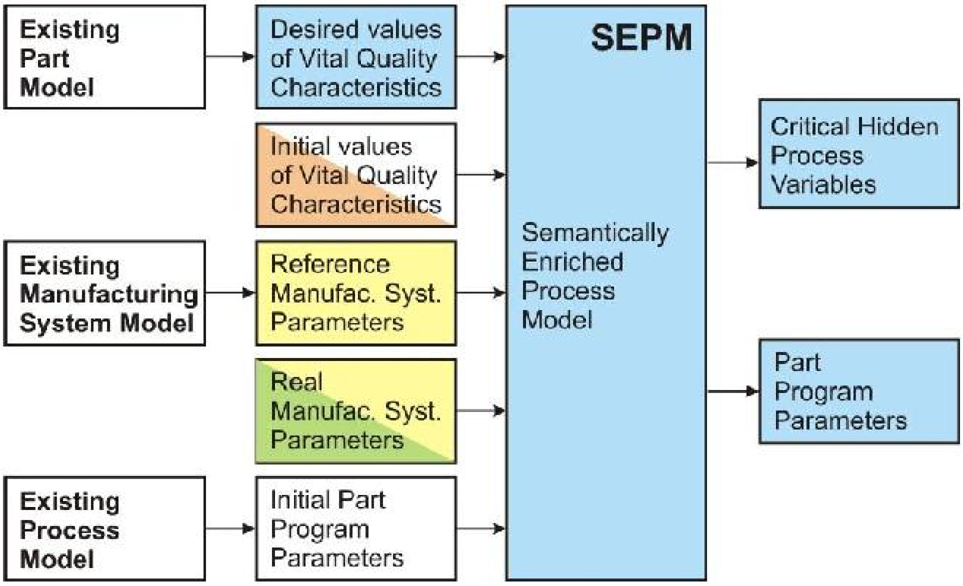


Figure 14: Semantically enriched Process Model

In the proposed approach, part quality errors (deviations from the reference part quality) are modelled and predicted as a function of the input process parameters, on-line process measurements and real manufacturing system states. According to this method, it is the reference part quality that indicates the desired ranges of values for the related vital quality characteristics (VQCs).

- A knowledge-based representation of the manufacturing system performance across the process chain.

  A method has been defined for specifying the reference manufacturing system performance as function of the process load (demand) as well as the physical limits of manufacturing system (see Figure 15); this allows to monitor deviations and, in critical cases, to suggest appropriate process re-planning actions.

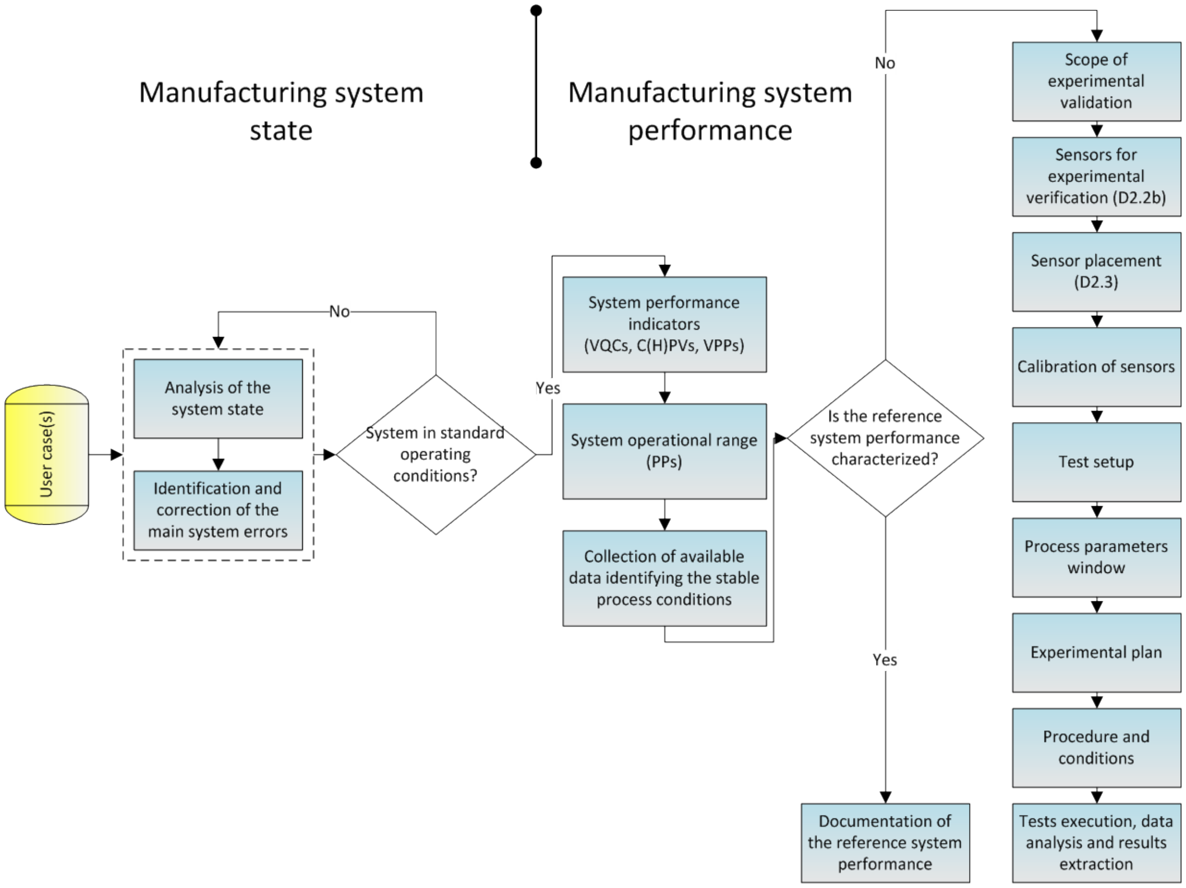


Figure 15: Procedure for defining reference manufacturing system performance

- A simulation-based sub-system that provides process re-planning suggestions across the multi-stage process chain by using the extracted knowledge from real-time measured data.

  Within WP6, an intelligent self-adaptation and self-optimization methodology has been developed (process parameters adjustments suggestions system, PPASS). The methodology relies always on fuzzy logic for part quality prediction, fault diagnosis and process parameters adjustment suggestions. Fuzzy logic has been chosen due to its ability to account for vagueness/imprecision and nonlinear behaviour, which are common characteristics to manufacturing processes and systems. In the fuzzy-nets approach, the relationships between the inputs and the outputs of the manufacturing process are described through a collection of fuzzy control rules involving linguistic variables rather than a complicated dynamic mathematical model (differential equations). The most evident benefit of the implementation of the fuzzy-nets controller is related to the real-time process adjustments and mid-term process re-planning based on predicted part quality characteristics.

  The fuzzy-nets system has two further subsystems i.e. the predictive system, operative on normal process conditions, and the fault diagnostic system (see Figure 16), active when anomalies in the process are detected.

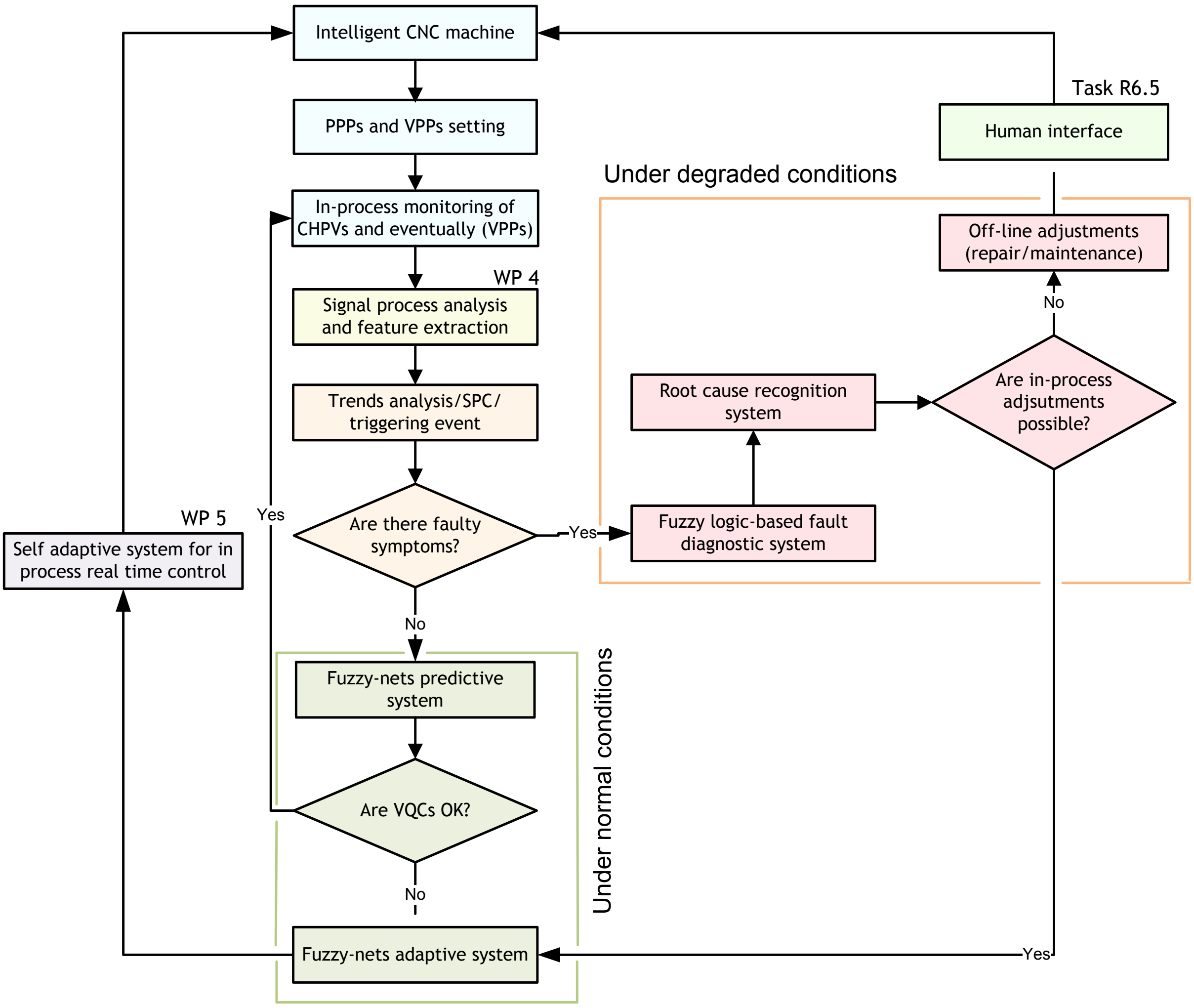


Figure 16: Main IFaCOM systems including the predictive and adaptive fuzzy-nets systems

Within WP6 also a set of human shop-floor user interfaces has been developed for the SIFDPS (in the following often referred as GUIs, graphical user interfaces).

3.7 WP7

WP7 has focused on the implementation of R&D results into the demonstrators of the Aerospace sector.

GKN

GKN produces, amongst many other products, Turbine Rear Frames (TRFs). The TRF is a part of a jet engine, and is manufactured by assembling multiple components together in a toroidal structure. Current production of TRFs is highly dependent on manual operations, while the company wants to decrease these manual operations and substitute them with automatic operations.
The IFaCOM demonstrator at GKN focuses on demonstrating the automatic assembly and tack welding of components of a TRF section.

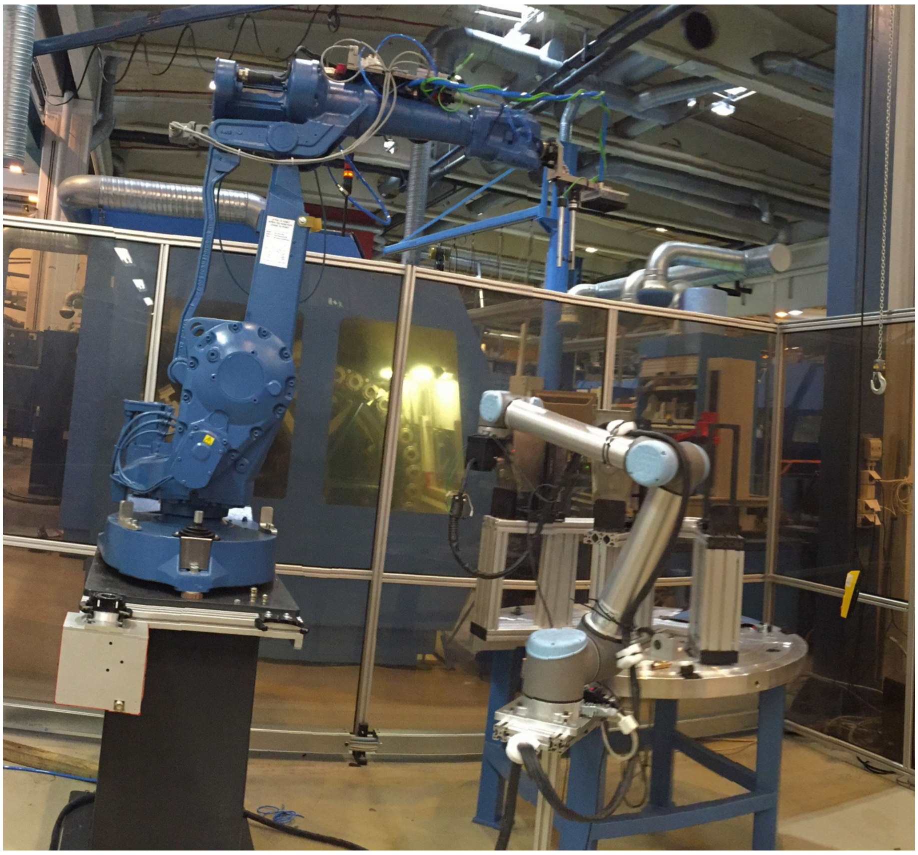


Figure 17: Final demonstrator setup at GKN

In the final setup (Figure 17, Figure 18), different subsystems interact together in order to cover all the steps required for obtaining the optimal result at the assembly, from a prediction system using intelligent algorithms for suggesting element configuration, to a cell formed by two robots, welding tools and sensors that demonstrates the physical feasibility of the IFaCOM concept with a TRF section. The demonstrator shows technology for changing a manual assembly process of TRFs into an automated process where the quality requirements are validated and verified. The goal of the automatic assembly process is to achieve a Turbine Rear Frame (TRF) within the drawing tolerances for surface offset in between the different segments, minimizing residual elastic stress in the part and maximizing the plastic strain.

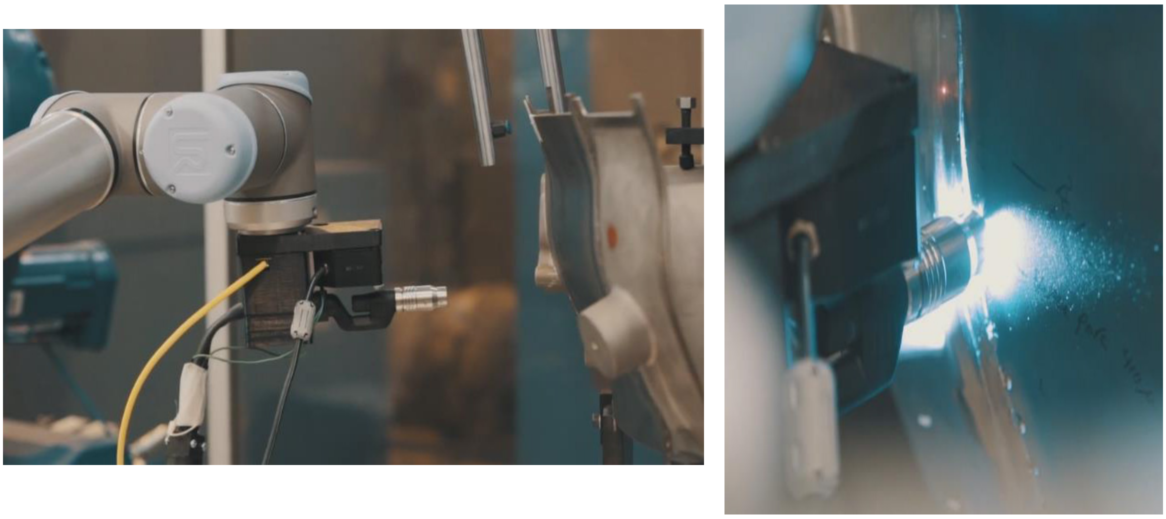


Figure 18: Automatic tack welding of the TRF at GKN

The GKN demo's system (Figure 19) analyses and uses data from multiple sensors in upstream operations, during the assembly process and uses the data in the actual assembly tack welding (Figure 18) as well as full seam welding. The new approach has a basis in collecting machining data (MAS), geometry data (MES), selecting the best fitting segments (ISP), collecting data from tack welding (ATW) and, if possible, from full seam welding (AP). This opens up for in-depth off line long-term analysis of the assembly process using knowledge from all the different steps of machining of segments (MAS), geometry of segments (MES), differential fit between selected segments (ISP), assembly sensor data (ATW) and if possible data from full seam welding (AP).

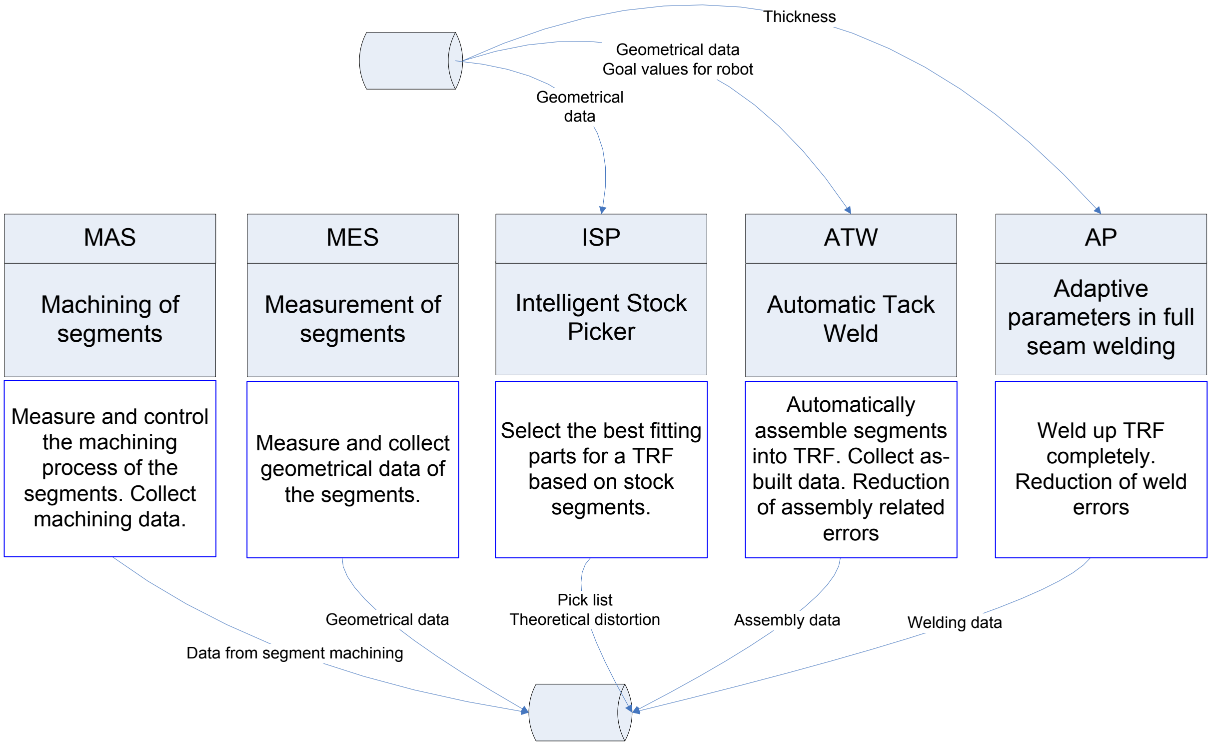


Figure 19: Overview of systems that interact in GKN's demonstrator

The IFaCOM Zero Defect approach described above, consisting of three control loops, in the GKN case had the following targets:

- For the short-term corrections, an automated system consisting of robots, sensors and a welding source is the central performer. The system assembles and tack welds aerospace Turbine Rear Frames automatically, measuring the process status in real-time and making decisions before applying the necessary corrections by analysing sensor measurements.
- An Intelligent Stock Picker (ISP, described in details below) covers the medium-term corrections loop, by calculating the optimal configuration of segments that forms a TRF. Once those geometries are measured, data is analysed and optimal combinations of components for the assembly are suggested. The selected components are picked and placed in optimal positions where they are assembled by the automated assembly system.
- The long-term corrections are performed by analysing the data collected by the sensors that are installed in the demonstrator. These data provides information on process trends and point to required improvements of the operation.

Diverse software tools have been used in the demonstrator, being mostly developed and programmed during the project with different programming languages (mostly C++ and Python).
The different software tools, are able to communicate among them and perform three main tasks in the demonstrator:

- Intelligent sorting of components using Genetic Algorithms.

The ISP is a genetic algorithm-based software tool that is able to calculate the different configurations of segments that can be assembled with the current stock (see Figure 20). Geometrical values of the components in stock at GKN are input to the ISP, and the program calculates all the possible configurations that can be obtained, as well as calculating the manufacturing cost of each configuration and the number of bends.
The goal is to minimize the residual stresses accumulated in the final TRF structure. For achieving this goal, the ISP calculated the configurations that minimize the bending of components; and selects components that need to be bent in regions that are easier for a robot to bend.

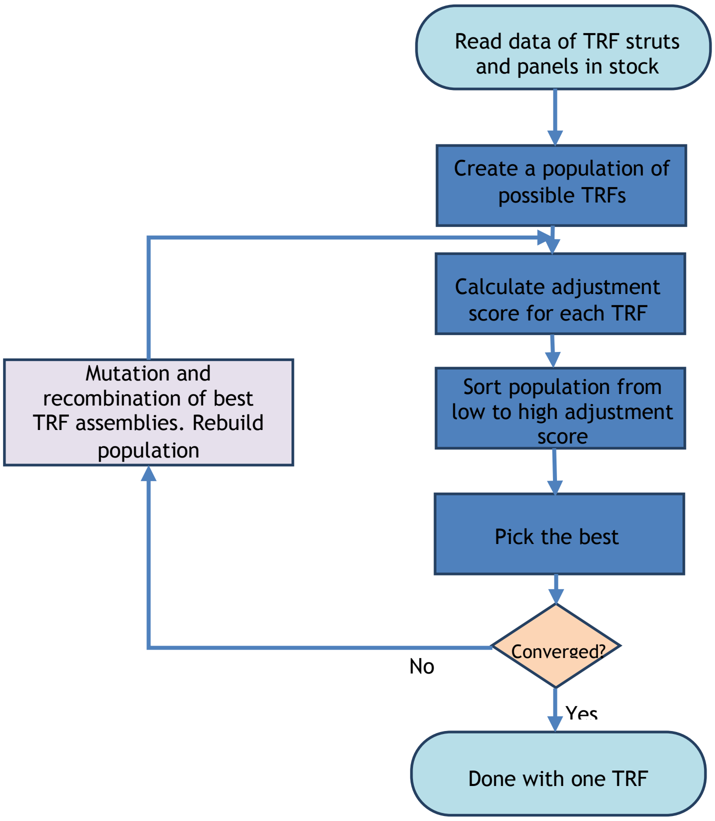


Figure 20: ISP flow chart

- Real-time control of robotic assembly and tack welding operation.
Controlling two robots by analysing the feedback provided by the different sensor systems in real-time is a demanding task that requires solid integration between all the different subsystems. This integration has been achieved by developing specific software that is able to control the different subsystems while orchestrating all the top-level operations needed for the system. The real-time robot control is implemented in the ROS (www.ros.org) framework, using the ROS Control project (Figure 21).
ROS has provided a flexible framework for testing different robots and routines.
Adjustment and tack welding operations require quasi real-time robot trajectory generations for adjusting the correct offset and welding the correct points. Every segment is different, and every point on the segments is located at an unknown position at the beginning of the operation.
The 'welding robot', having a laser distance sensor and a welding torch attached to its end-effector, has to orient itself in order to measure the offset between the panels from the correct perspective. The welding torch has to be located strictly perpendicular to the point to be tack welded, as well as placed in the middle of the gap of the two parts that are to be tack welded. These conditions lead to the requirement for the robot orientation to be defined in real-time for every step of the operation. For this, the welding robot uses a laser distance sensor. The robot moves its arm, while the sensor collects profile data of the segments. The set of data is analysed by the PC and creates a virtual approximation of the

profile position and orientation. The robot then is reoriented for getting the correct data and welding the points correctly.

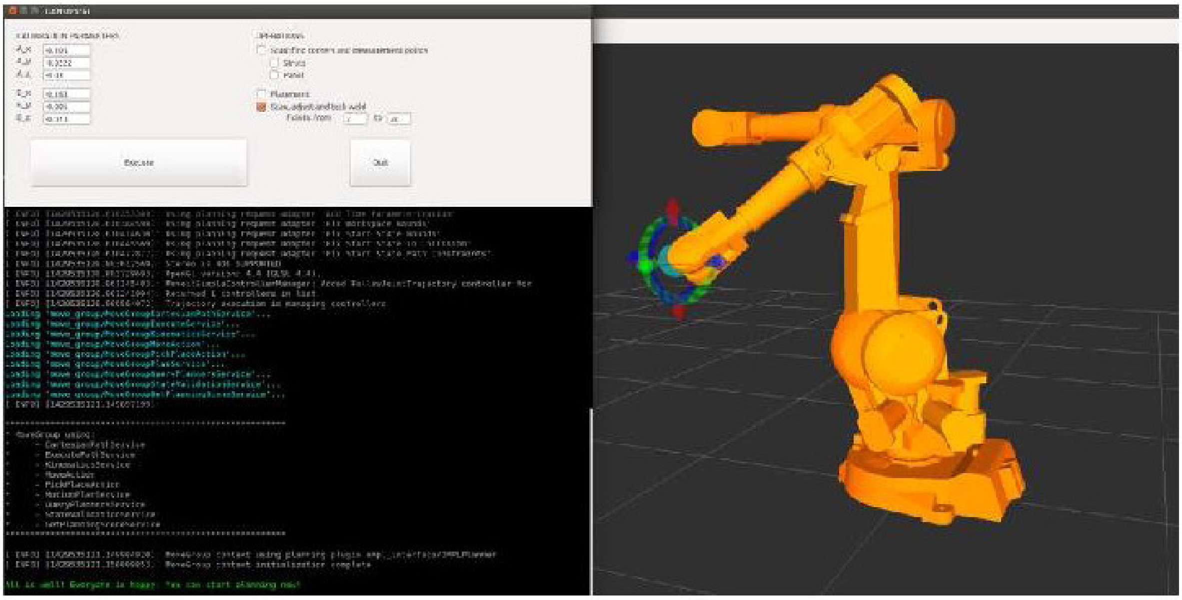


Figure 21: Visualization of ROS motion planning and real-time robot trajectory planning on GKN’s ABB robot

The steps of the operation are sketched in Figure 22, where in blue are shown the tasks of welding robot and in brown those of the other robot (bending and placement). The last task is iterative and performed several times by both robots until all the tack welds connecting the segments are completed.

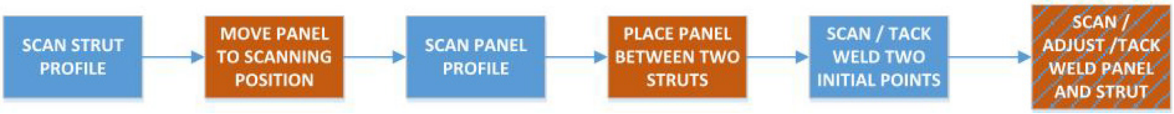
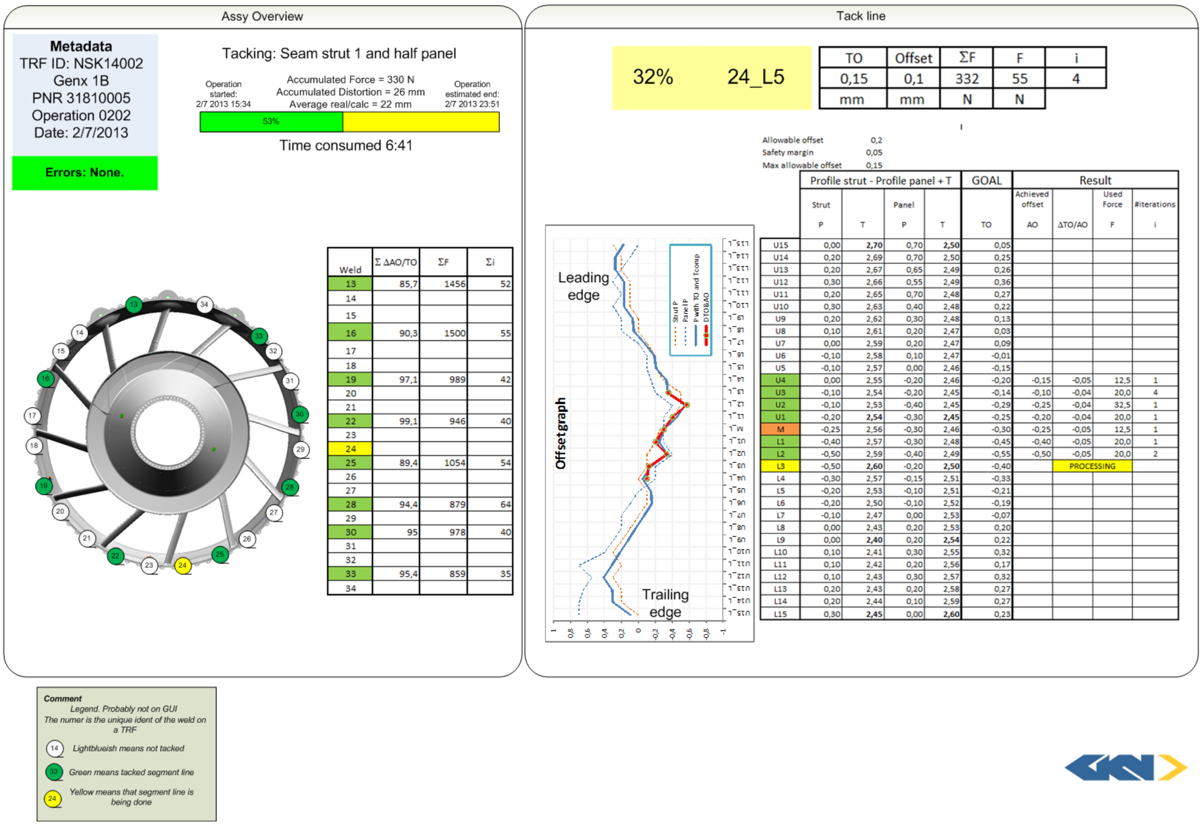


Figure 22: Robot scanning and adjustment sequence

- Visualization by operator of operation status and progress (Graphical User Interface – GUI, see Figure 23).
  The GUI gets updated in real-time with the information collected by the sensors in the robotic adjustment and tack welding operations.
  In the GUI is possible to visualize the time elapsed since the beginning of the process, the accumulated force, the total distortion introduced for bending the panels (up left).
  An overview of the full TRF status is also provided, with colours indicating the progress of the welding process (TRF picture down left, yellow – currently welding, green – done, white – not welded). Also, the operator can check the segment line progress (up right) and in details all the segment joint lines, identified with the weld number (table on the right). Finally, also the actual measurements from the laser sensors and the offset from the nominal profile are displayed in the picture on the right.



Assy Overview

Metadata
TRF ID: NSK14002
Genx 1B
PNR 31810005
Operation 0202
Date: 2/7/2013

Errors: None.

Tacking: Seam strut 1 and half panel

Operation started: 2/7 2013 15:34

Accumulated Force = 330 N
Accumulated Distortion = 26 mm
Average real/calc = 22 mm

Operation estimated end: 2/7 2013 23:51

53%

Time consumed 6:41

Weld	Σ ΔAO/TO	ΣF	Σi
13	85,7	1456	52
14			
15			
16	90,3	1500	55
17			
18			
19	97,1	989	42
20			
21			
22	99,1	946	40
23			
24			
25	89,4	1054	54
26			
27			
28	94,4	879	64
29			
30	95	978	40
31			
32			
33	95,4	859	35
34			

Tack line

32% 24_L5

TO	Offset	ΣF	F	i
0,15	0,1	332	55	4
mm	mm	N	N	

Allowable offset 0,2
Safety margin 0,05
Max allowable offset 0,15

	Profile strut - Profile panel + T				GOAL	Result			
	Strut P	T	Panel P	T	TO	Achieved offset AO	ΔTO/AO	Used Force F	#iterations i
U15	0,00	**2,70**	0,70	**2,50**	0,05				
U14	0,20	2,69	0,70	2,50	0,25				
U13	0,20	2,67	0,65	2,49	0,26				
U12	0,30	2,66	0,55	2,49	0,36				
U11	0,20	2,65	0,70	2,48	0,27				
U10	0,30	2,63	0,40	2,48	0,22				
U9	0,20	2,62	0,30	2,48	0,13				
U8	0,10	2,61	0,20	2,47	0,03				
U7	0,00	2,59	0,20	2,47	0,09				
U6	-0,10	2,58	0,10	2,47	-0,01				
U5	-0,10	2,57	0,00	2,46	-0,15				
U4	0,00	2,55	-0,20	2,46	-0,20	-0,15	-0,05	12,5	1
U3	-0,10	2,54	-0,20	2,45	-0,14	-0,10	-0,04	20,0	4
U2	-0,10	2,53	-0,40	2,45	-0,29	-0,25	-0,04	32,5	1
U1	-0,20	**2,54**	-0,30	**2,45**	-0,25	-0,20	-0,04	20,0	1
M	-0,25	2,56	-0,30	2,46	-0,30	-0,25	-0,05	12,5	1
L1	-0,40	2,57	-0,30	2,48	-0,45	-0,40	-0,05	20,0	1
L2	-0,50	2,59	-0,40	2,49	-0,55	-0,50	-0,05	20,0	2
L3	-0,50	**2,60**	-0,20	**2,50**	-0,40		PROCESSING		
L4	-0,30	2,57	-0,15	2,51	-0,33				
L5	-0,20	2,53	-0,10	2,51	-0,21				
L6	-0,20	2,50	-0,10	2,52	-0,19				
L7	-0,10	2,47	0,00	2,53	-0,07				
L8	0,00	2,43	0,20	2,53	0,20				
L9	0,00	**2,40**	0,20	**2,54**	0,22				
L10	0,10	2,41	0,30	2,55	0,32				
L11	0,10	2,42	0,20	2,56	0,17				
L12	0,10	2,43	0,30	2,57	0,32				
L13	0,20	2,43	0,20	2,58	0,27				
L14	0,20	2,44	0,10	2,59	0,27				
L15	0,30	**2,45**	0,00	**2,60**	0,23				

Comment
Legend. Probably not on GUI
The numer is the unique ident of the weld on a TRF
14 *Lightblueish means not tacked*
33 *Green means tacked segment line*
24 *Yellow means that segment line is being done*

Figure 23: GKN's GUI

EMA

Europea Microfusioni Aerospaziali (EMA), part of the Rolls Royce group is a precision investment castings foundry for the production of turbine blades, vanes and component for the most modern jet-engines to civil and defence aerospace and power generation engines. EMA's products are obtained using is the "lost wax" process and using mainly Ni-based superalloys. Ceramic inclusions (see Figure 24) problems are particularly relevant for the investment casting technology and represent one of the main sources of scraps in foundries.

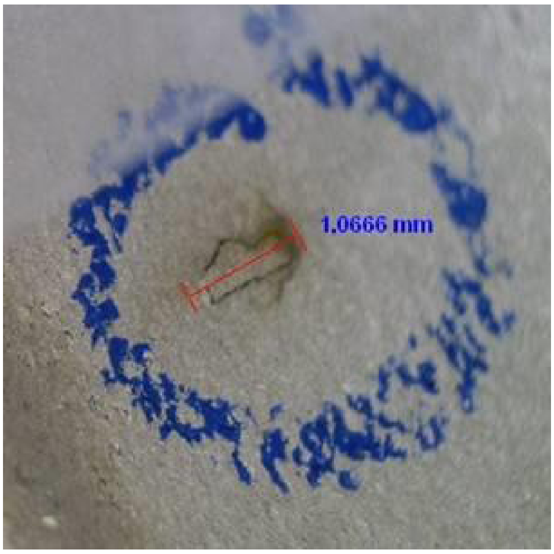


Figure 24: Ceramic inclusion

Therefore, the aim of the EMA's demonstrator is to achieve more effective control on the ceramic shell mould and particularly a more effective correction of the ceramic primary slurry that ensure the best final quality of the superalloy components in the long run.
The IFaCOM focus was restricted only to the shell making process (see Figure 25), mainly targeting the evaluation of the characteristics of the ceramic primary slurry and the final status of the ceramic shell, taking in account the final status of the superalloy components.

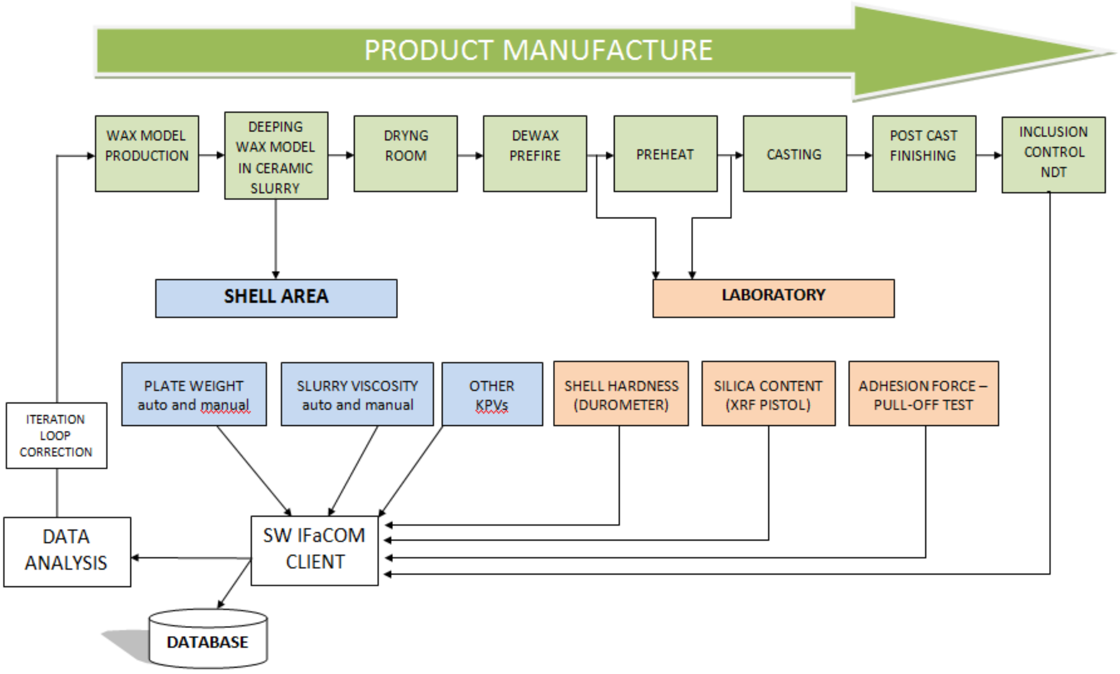


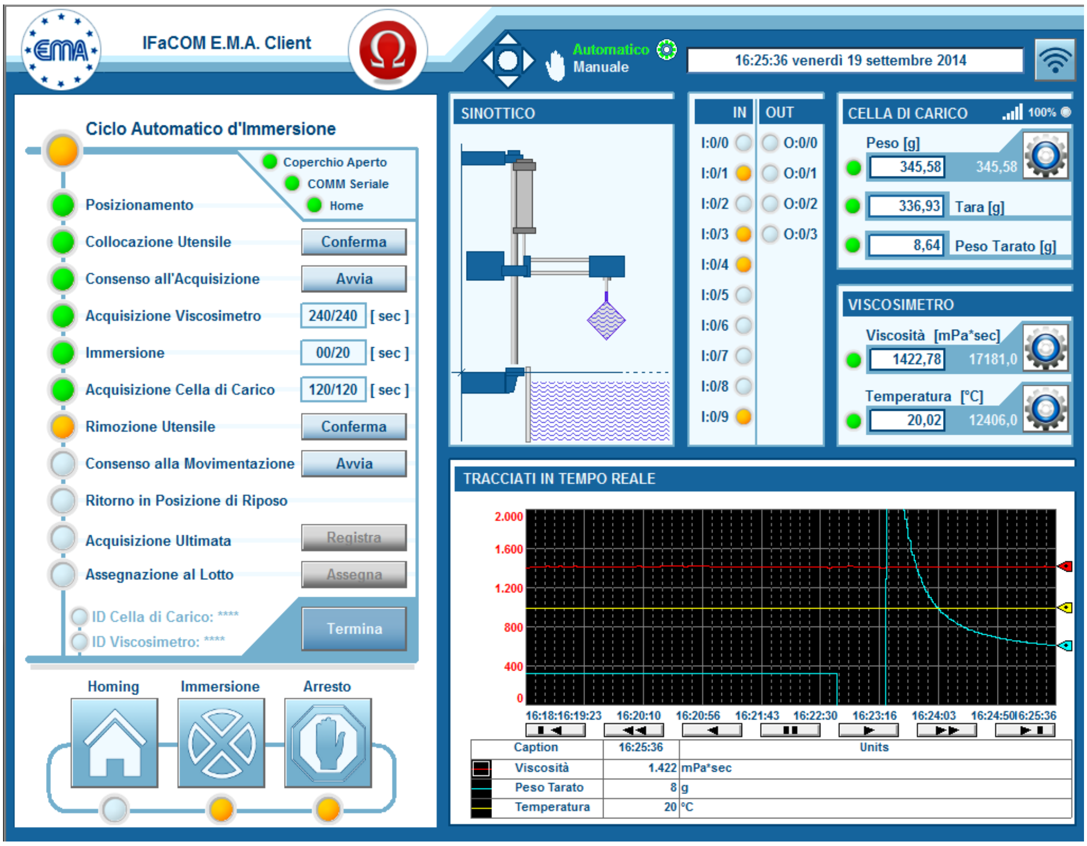
Figure 25: IFaCOM focus, the shell making process

Adapting the IFaCOM approach to the EMA's shell making process is challenging due to the fact that several measurements can be only performed offline and/or at the end of the full investment casting process; moreover, all the time scales of data acquisition are considerably different, ranging from a few minutes (for straightforward on-site automatic measurements), to a few hours (for off-site chemical laboratory surveys) and few days for final characteristics of the shell mould.
All these things considered, the IFaCOM strategy in the EMA's case involved:

- a robust control of the industrial manufacturing of the ceramic shells of one aeronautical vane component in the production line, by means of a focused monitoring of the primary slurry parameters and additional control of the ceramic shell quality that are not normally actuated during standard production cycles.
- in-line and an off-line data process acquisition (primary slurry parameters, shell mechanical characteristics and inclusion scrap rate of the components) and storage in a dedicated database.
- statistical and cognitive systems: Statistical Process Control (SPC) & Neural Networks data analysis with the aim to find the correlations between the measured Key Process Variables and the Target Variable (output quality parameter) represented by the inclusion scrap rate.

In the EMA's case, due to the complexity and the size of the production plant and machineries, practically no test could be performed in the laboratory and activities; measurements and analyses had to be carefully planned and carried out directly on the real (working) production line, while real parts were produced for the customers.
With all these constraints, the IFaCOM approach was tailored to the EMA's case showing both long-term and short-term control loops

- Short-term loop: real-time control of the shell making process through the introduction of new sensors and new equipment, the automation of manual measurement processes (see Figure 26 and 27) and the integration of all the solutions.



IFaCOM E.M.A. Client

Automatico
Manuale

16:25:36 venerdì 19 settembre 2014

Ciclo Automatico d'Immersione

Coperchio Aperto
COMM Seriale
Home

Posizionamento
Collocazione Utensile
Consenso all'Acquisizione
Acquisizione Viscosimetro 240/240 [sec]
Immersione 00/20 [sec]
Acquisizione Cella di Carico 120/120 [sec]
Rimozione Utensile
Consenso alla Movimentazione
Ritorno in Posizione di Riposo
Acquisizione Ultimata
Assegnazione al Lotto

ID Cella di Carico: ****
ID Viscosimetro: ****

CELLA DI CARICO 100%

Peso [g] 345,58 345,58
336,93 Tara [g]
8,64 Peso Tarato [g]

VISCOSIMETRO

Viscosità [mPa*sec] 1422,78 17181,0
Temperatura [°C] 20,02 12406,0

Caption	16:25:36	Units
Viscosità	1.422	mPa*sec
Peso Tarato	8	g
Temperatura	20	°C

Figure 26: Plate weight automated data acquisition (software)

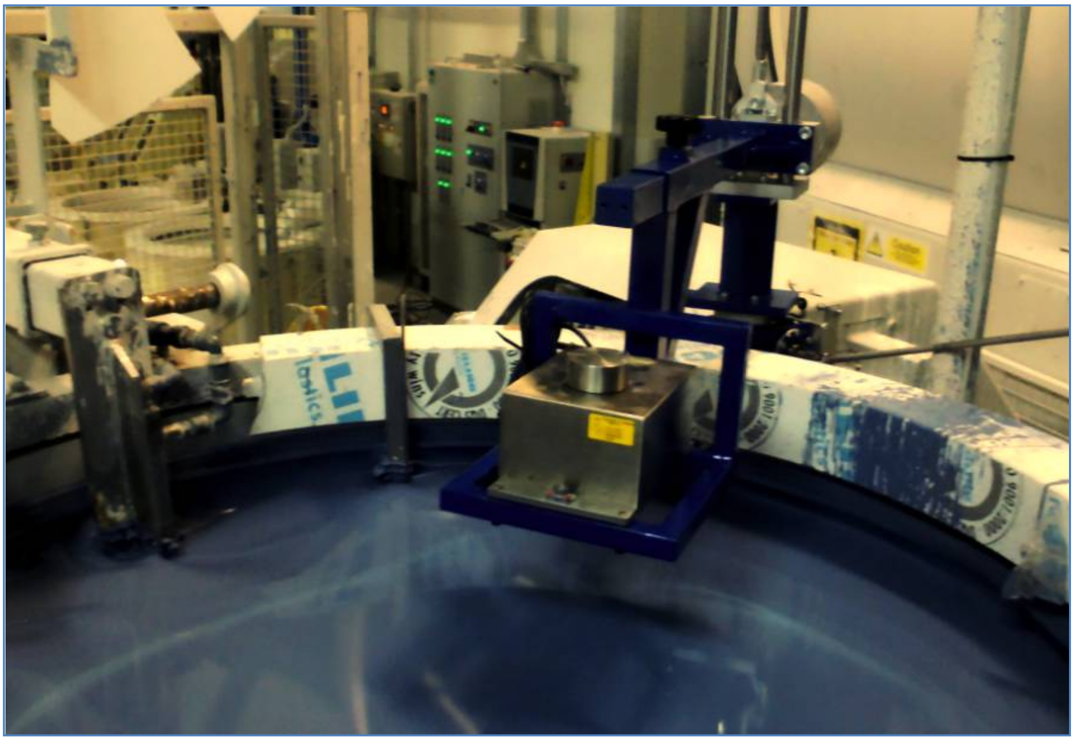


Figure 27: Plate weight automated data acquisition (Hardware)

Several sensors have been employed for the acquisition of some physical-chemical parameters on the primary equiassic slurry such as viscosity, temperature, plate weight (indirect measurement of the density).

- Long-term loop: process long-term optimization system based on a neural network approach.

  This approach relies on the continuously updated sensor data coming from the in-line sensors mentioned above and the post process analyses (silica content, shell mechanical hardness, adhesion of primary to secondary shell layers, pH, etc.). The neural network analyser developed within the project constantly evaluates and updates the correlation between product quality and the primary slurry condition. This allows to define the reference part quality and to extrapolate the optimal slurry characteristics suggesting possible corrections to the slurry composition. As mentioned above, this process is dynamic, and allows a long-term optimization of the product quality based on a constantly updated dataset and an increasingly more robust correlation and prediction capabilities

The IFaCOM system implemented in the EMA's demonstrator performs a hybrid data collection (partly online, partly offline) and data storage is done on a dedicated SQL database, developed during the project.
After the acquisition, a sensor vector (a .csv file, with all data) is generated (see Figure 28). This file represents the input for the successive IFaCOM Processing Algorithms segment. On the grounds of a neural network analysis, this module predicts optimal values for the slurry parameters to be processed for the successive mould generation.
The suggested values and the related corrections, based both on indications provided by the neural network analysis and by EMA's tested internal formulae, are presented on a PC panel through the IFaCOM GUI, shown in Figure 29 (reported values are not real). The visualization of the classical correction allows to compare standard values with neural networks' suggestions in order to double check artificial intelligence outputs and giving the operator the possibility to choose the best correction values for the primary slurry.

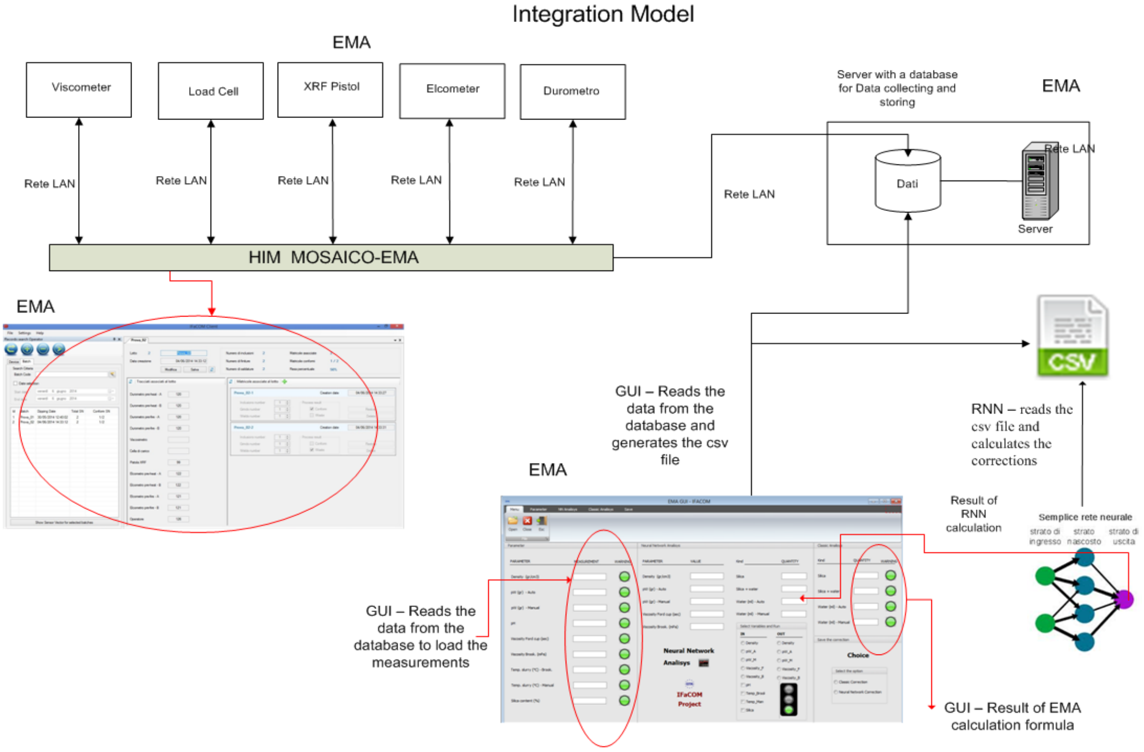
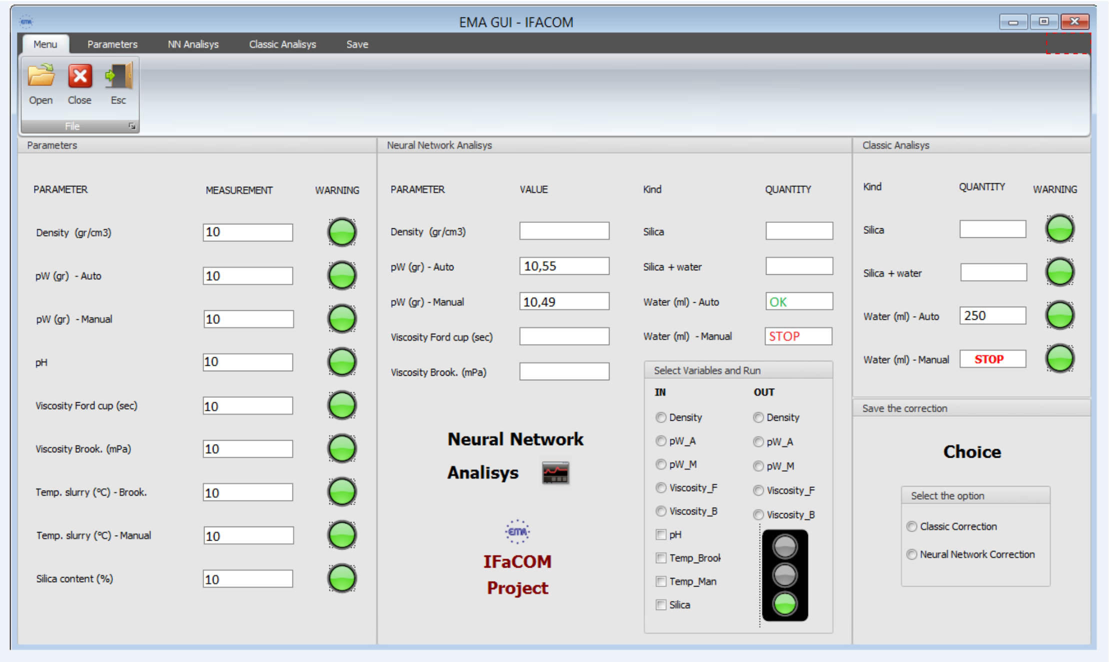


Figure 28: EMA's demo software architecture



Parameters

PARAMETER	MEASUREMENT	WARNING
Density (gr/cm3)	10	●
pW (gr) - Auto	10	●
pW (gr) - Manual	10	●
pH	10	●
Viscosity Ford cup (sec)	10	●
Viscosity Brook. (mPa)	10	●
Temp. slurry (°C) - Brook.	10	●
Temp. slurry (°C) - Manual	10	●
Silica content (%)	10	●

Neural Network Analisys

PARAMETER	VALUE
Density (gr/cm3)	
pW (gr) - Auto	10,55
pW (gr) - Manual	10,49
Viscosity Ford cup (sec)	
Viscosity Brook. (mPa)	

Kind	QUANTITY
Silica	
Silica + water	
Water (ml) - Auto	OK
Water (ml) - Manual	STOP

Select Variables and Run

IN	OUT
○ Density	○ Density
○ pW_A	○ pW_A
○ pW_M	○ pW_M
○ Viscosity_F	○ Viscosity_F
○ Viscosity_B	○ Viscosity_B
☐ pH	
☐ Temp_Brool	
☐ Temp_Man	
☐ Silica	

Classic Analisys

Kind	QUANTITY	WARNING
Silica		●
Silica + water		●
Water (ml) - Auto	250	●
Water (ml) - Manual	STOP	●

Save the correction

Select the option

○ Classic Correction
○ Neural Network Correction

Figure 29: EMA’s GUI

3.8 WP8

WP8 has focused on the implementation of R&D results into the demonstrators of the Machine tools sector.

ALESAMONTI

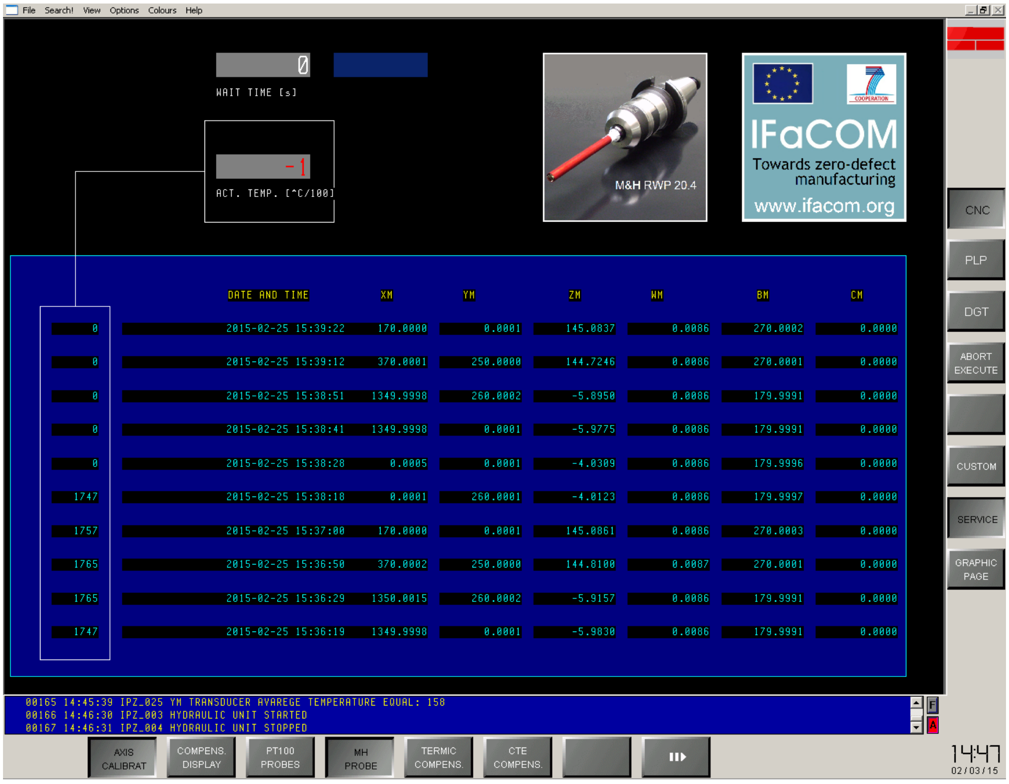
Alesamonti is a manufacturer of boring/milling machine tools (Figure 30). Every structural component of its machines is manufactured internally, often using Alesamonti’s machine tools for boring/milling processes.

Figure 30: Alesamonti's MAF45 demo machine tool

Figure 31: Alesamonti’s demo thermal chamber

Some of their components, produced in small batches, are quite big while their tolerances (flatness, squareness and parallelism) are typically within 50 µm. For making the first part right, and avoid/reduce expensive and time consuming reworking and manual fitting of their components, they need to perform a thorough control of their processes.
Therefore, their focus within the IFaCOM project has been on isolating and deeply analysing possible sources of geometric errors (part, machine, process) and to develop tools for controlling their processes, increasing their chances to have a zero defect manufacturing.
In particular, Alesamonti’s main investigations during the project have been on minimizing the effect of thermally and mechanically induced part distortions; project work has been carried out in the Alesamonti’s dedicated test chamber (Figure 31), developed during the previous SOMMACT EU project which is equipped with a MAF45 machine (Figure 30) and allows to control the room temperature and simulate different thermal operating conditions.
The system implemented within the project follows the three-loops IFaCOM scheme with a

- Short-term loop: quasi real-time compensation of thermal and clamping effects
  After several tests performed on the machine and on the workpieces in its test chamber, including also the development and test of a dedicated tool wear monitoring system, Alesamonti has developed a dedicated quasi real-time control system which allows to compensate part deformations and deriving tolerance errors due to several causes. The system relies on the application of several sensors (temperature, cutting force, power, etc.) and on improved control algorithms implemented in the FIDIA machine’s CNC. In particular, the system allows to compensate mechanical deformation induced on the workpiece by clamping forces (core of a patent application, see Figure 32) and thermal deformations of the workpiece and of the machine.
  The system foresees workpiece thermal status measurements (Figure 32) performed at programmed positions, defined in the part program, using a wireless temperature probe; the compensation is automatic (applied by the CNC) when some conditions are met, otherwise some corrective actions are proposed to the operator.



	DATE AND TIME	XM	YM	ZM	WM	BM	CM
0	2015-02-25 15:39:22	170.0000	0.0001	145.0837	0.0086	270.0002	0.0000
0	2015-02-25 15:39:12	370.0001	250.0000	144.7246	0.0086	270.0001	0.0000
0	2015-02-25 15:38:51	1349.9998	260.0002	-5.8950	0.0086	179.9991	0.0000
0	2015-02-25 15:38:41	1349.9998	0.0001	-5.9775	0.0086	179.9991	0.0000
0	2015-02-25 15:38:28	0.0005	0.0001	-4.0309	0.0086	179.9996	0.0000
1747	2015-02-25 15:38:18	0.0001	260.0001	-4.0123	0.0086	179.9997	0.0000
1757	2015-02-25 15:37:00	170.0000	0.0001	145.0861	0.0086	270.0003	0.0000
1765	2015-02-25 15:36:50	370.0002	250.0000	144.8100	0.0087	270.0001	0.0000
1765	2015-02-25 15:36:29	1350.0015	260.0002	-5.9157	0.0086	179.9991	0.0000
1747	2015-02-25 15:36:19	1349.9998	0.0001	-5.9830	0.0086	179.9991	0.0000

```
00165 14:45:39 IPZ_025 YM TRANSDUCER AVAREGE TEMPERATURE EQUAL: 158
00166 14:46:30 IPZ_003 HYDRAULIC UNIT STARTED
00167 14:46:31 IPZ_004 HYDRAULIC UNIT STOPPED
```

Figure 32: Workpiece temperature measurement outputs in the IFaCOM GUI

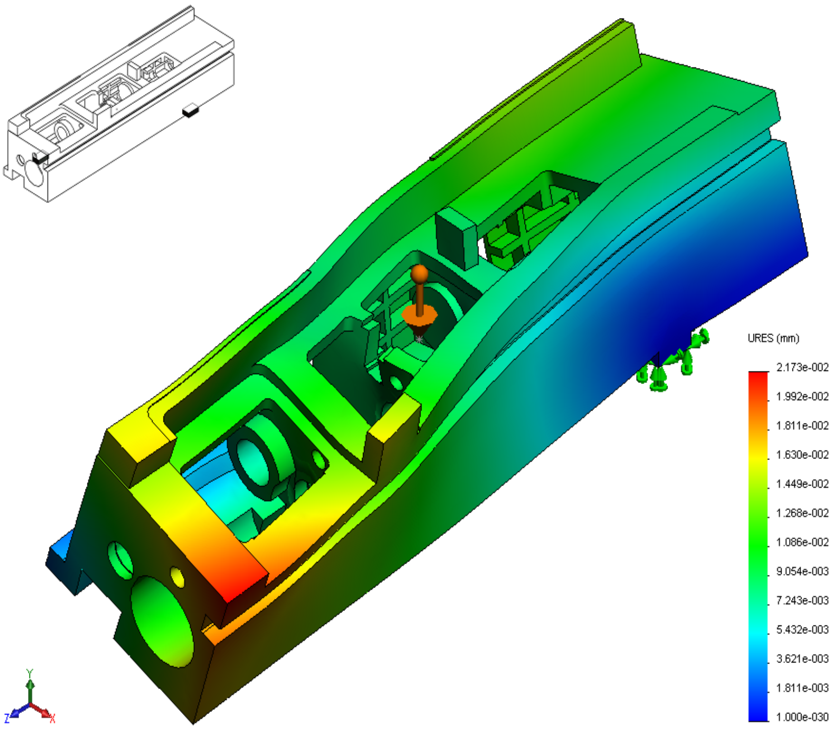


Figure 33: FEM simulation of clamping effects

- Medium and long-term loop: application of small batch Statistical Process Control
  The application of the medium and long-term control loop in the Alesamonti's case show some challenges in the long-term process optimization, due to difficulty of developing learning, generalising and forecasting capabilities from small and single batch productions data.
  Therefore, the company developed a dedicated methodology (see Figure 34 and also WP3 details, above) for adapting the statistical process control to its production, and make processes repeatable and stable thus reducing variability of product characteristics also for small and single batches.

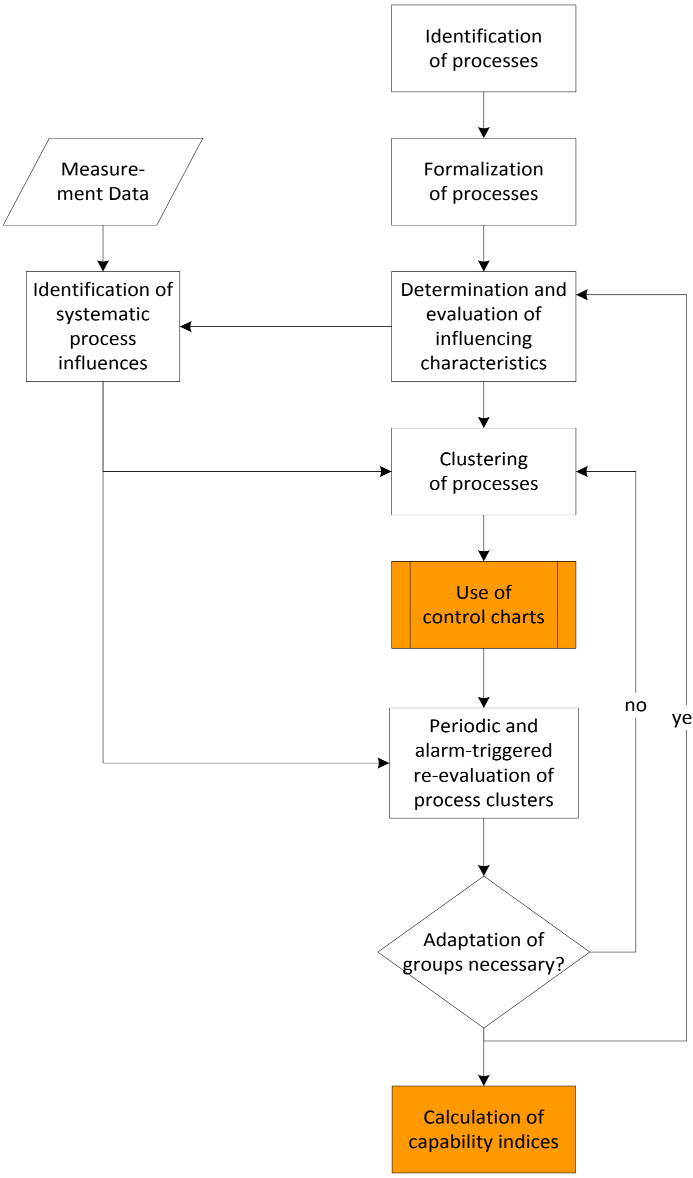
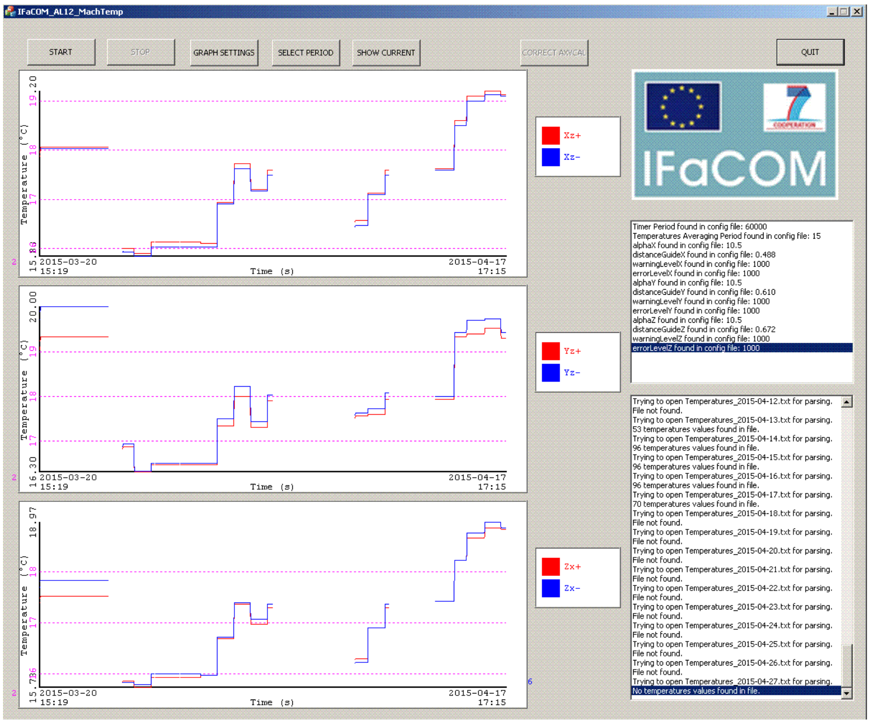


Figure 34: Procedure for the application of SPC to small- and single-batch production

The system developed during the project relies on the integration of different devices (sensors, monitoring systems) on the AT120 demo machine, and has required an ad-hoc upgrade of the FIDIA CNC software, including the development of new control algorithms based on the installed hardware inputs and applied methodologies. Customised user interfaces (IFaCOM GUI, see Figure 33 and Figure 35) have been also included in the existing FIDIA's interface.



```
Timer Period found in config file: 60000
Temperatures Averaging Period found in config file: 15
alphaX found in config file: 10.5
distanceGuideX found in config file: 0.488
warningLevelX found in config file: 1000
errorLevelX found in config file: 1000
alphaY found in config file: 10.5
distanceGuideY found in config file: 0.610
warningLevelY found in config file: 1000
errorLevelY found in config file: 1000
alphaZ found in config file: 10.5
distanceGuideZ found in config file: 0.672
warningLevelZ found in config file: 1000
errorLevelZ found in config file: 1000
```

```
Trying to open Temperatures_2015-04-12.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-13.txt for parsing.
53 temperatures values found in file.
Trying to open Temperatures_2015-04-14.txt for parsing.
96 temperatures values found in file.
Trying to open Temperatures_2015-04-15.txt for parsing.
96 temperatures values found in file.
Trying to open Temperatures_2015-04-16.txt for parsing.
96 temperatures values found in file.
Trying to open Temperatures_2015-04-17.txt for parsing.
70 temperatures values found in file.
Trying to open Temperatures_2015-04-18.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-19.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-20.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-21.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-22.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-23.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-24.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-25.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-26.txt for parsing.
File not found.
Trying to open Temperatures_2015-04-27.txt for parsing.
No temperatures values found in file.
```

Figure 35: Alesamonti's GUI. Thermal deformation of linear axes guides; temperature monitoring.

STRECON

Strecon has developed a new machine system for surface polishing of industrial tools and machine components. The technology is based on an industrial robot and known as RAP (Robot Assisted Polishing).

Figure 36: Strecon's Robot Assisted Polishing machine

The RAP machine (Figure 36) consists of a part-holding spindle and a polishing module with controlled contact force held by an industrial robot, providing for spatial movements in the machine workspace. The spindle, driven by a direct-drive servomotor, provides either for rotation of an axisymmetric part or indexing of a stationary part. The polishing module with air-pressure controlled contact force provides either an oscillating (reciprocating) linear tool movement or a rotating tool movement (see Figure 37).

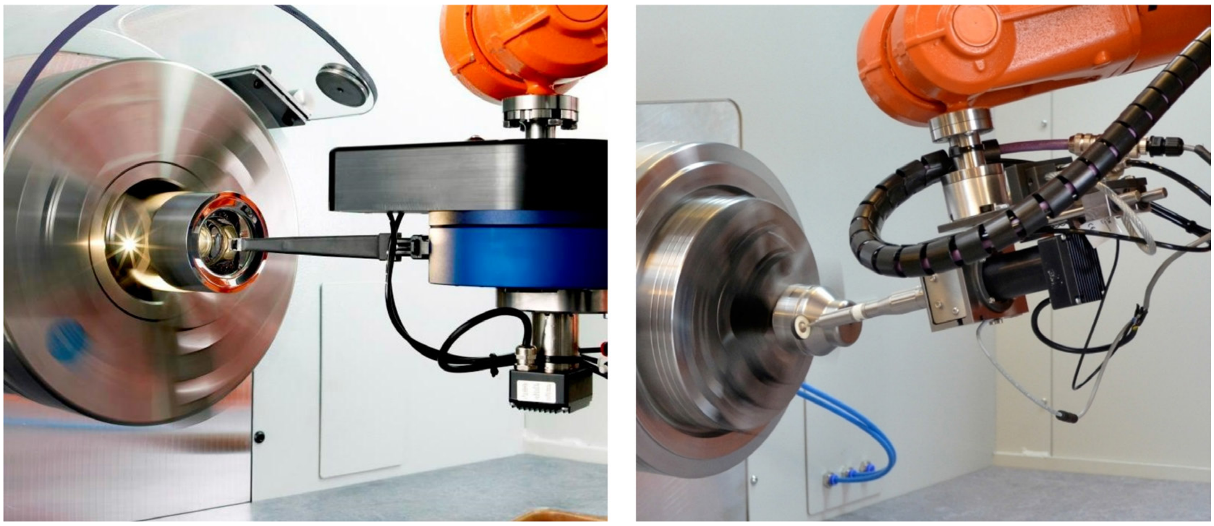


Figure 37: Polishing module providing oscillating linear (left) and rotating tool movement (right).

In the RAP, a generic part is polished in a number of process steps using increasingly finer abrasives, as depicted in Figure 38. The determination of the optimal time for change of the abrasive media between the polishing steps (process End Point Detection – EPD) is a key and time consuming issue.

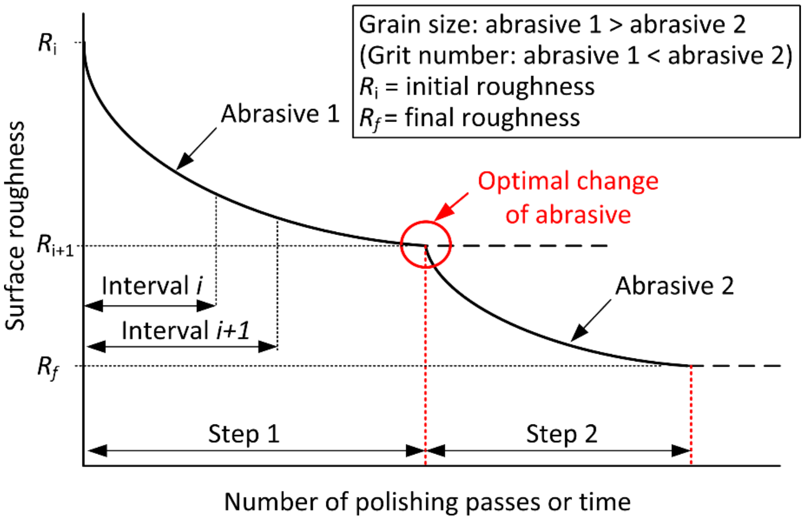


Figure 38: Two discrete steps of a typical sequential RAP process showing the optimal time for change of the polishing abrasive media

The objective of the Strecon's demonstrator is to apply the technologies required to fully automate the polishing process.

The IFaCOM system customised on the Strecon's application case foresees

- A short-term control loop for process state monitoring
  Through the application of several sensors (force, acoustic emission, power, see Figure 39), relevant process parameters are acquired and process state is quickly assessed; the control loop is based on simple algorithms for the detection of abnormal variations of some features of the acquired signals, symptoms of process anomalies and malfunctions. This approach allows minimizing defects due to sudden phenomena like tool breakage.

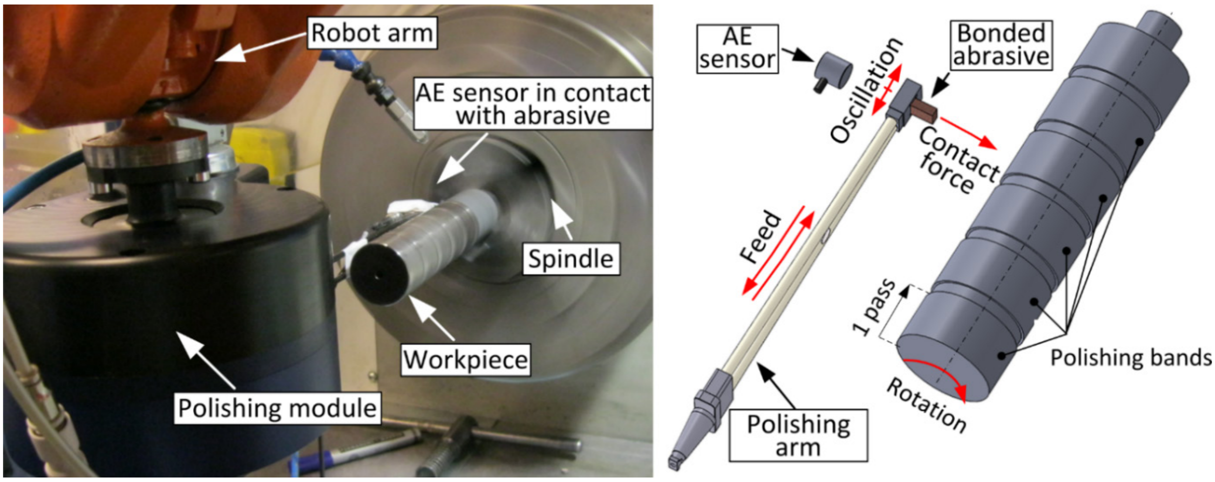


Figure 39: Experimental setup (left) and indication of AE sensor placement with the main process movements (right).

- Medium and long-term control loop
  This control loop relies both on the data provided by the sensors mentioned above and on the application of an in-line Quality Control system for surface characterization (roughness, gloss, see Figure 40) and local defects identification.

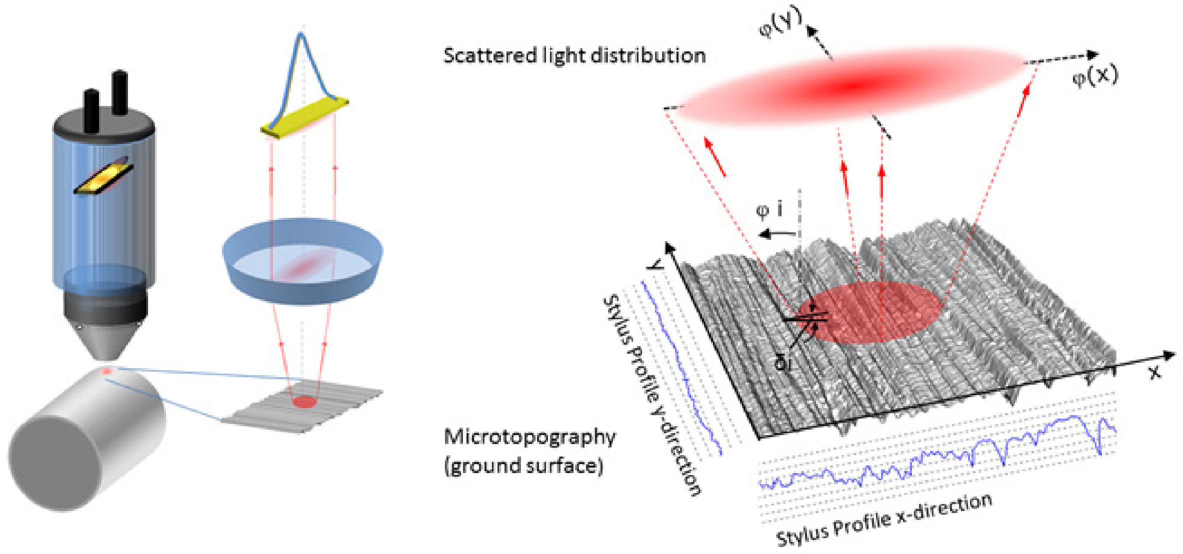


Figure 40: Measuring principle of Non-Contact Surface Metrology by means of Light Scattering (courtesy of Optosurf Gmbh)

The determination of the right moment for changing to finer abrasive between polishing steps relies on the correlation between part quality characteristics (surface roughness) and sensor signal features. The correlation has been studied and several algorithms have been developed and tested within the project (Figure 41).

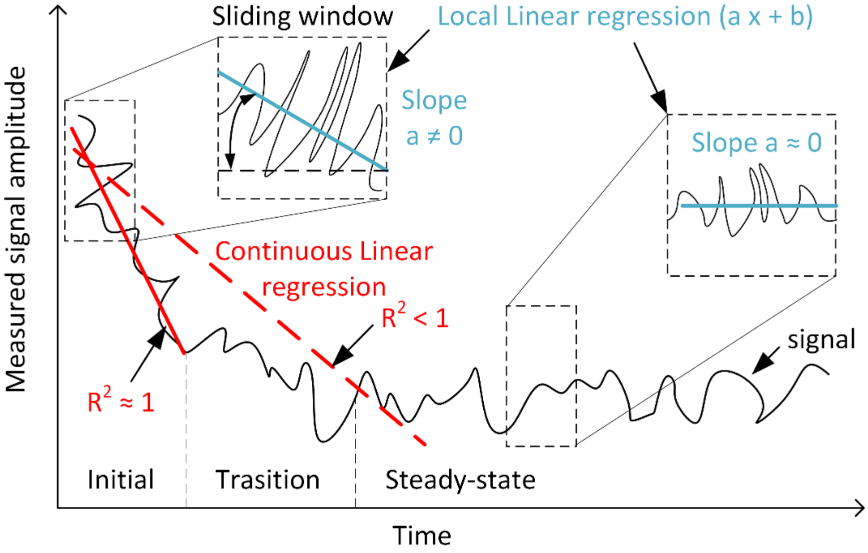
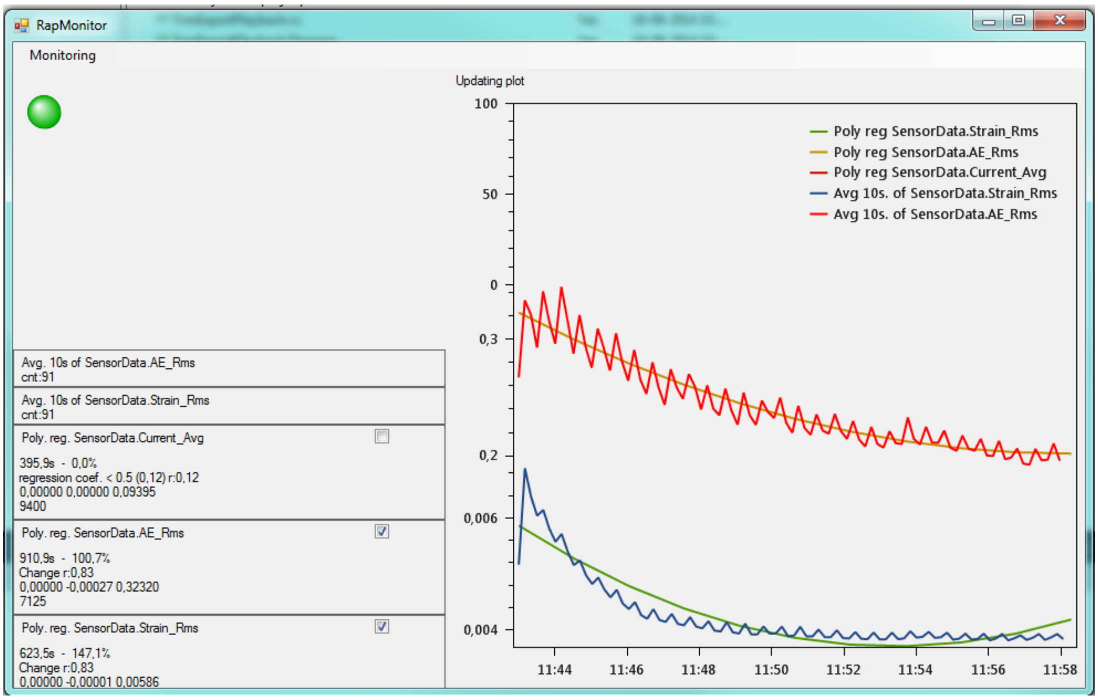


Figure 41: Schematics of one of the tested algorithms, regression-based

The software applied in the Strecon's case is based on the existing control software of the robot, enriched with the IFaCOM algorithms and user interface (see Figure 42).

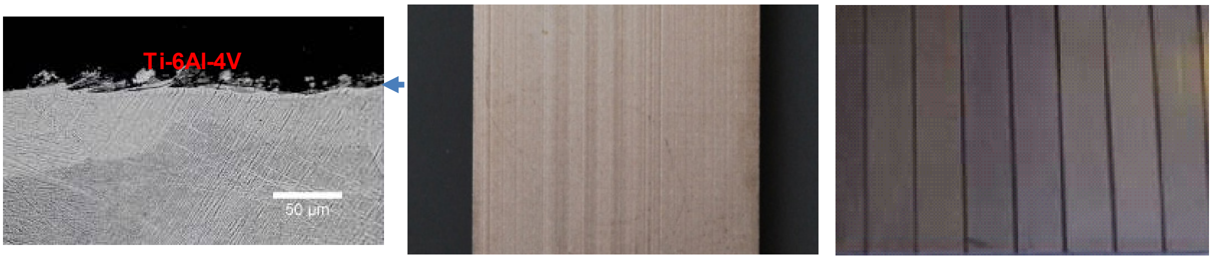


```
Avg. 10s of SensorData.AE_Rms
cnt:91

Avg. 10s of SensorData.Strain_Rms
cnt:91

Poly. reg. SensorData.Current_Avg        ☐

395,9s  -  0,0%
regression coef. < 0.5 (0,12) r:0,12
0,00000 0,00000 0,09395
9400

Poly. reg. SensorData.AE_Rms             ☑

910,9s  -  100,7%
Change r:0,83
0,00000 -0,00027 0,32320
7125

Poly. reg. SensorData.Strain_Rms         ☑

623,5s  -  147,1%
Change r:0,83
0,00000 -0,00001 0,00586
```

Figure 42: RAP monitoring GUI

AGIE CHARMILLES

Georg Fischer Agie Charmilles (GFAC) is a manufacturer of high precision machine tools which use a metallic wire (electrode) to cut a programmed contour in a workpiece (wire EDM, Electric Discharge Machining).
Current practice of WEDM is not defect-free and still a number parts produced by WEDM processes are rejected due to surface quality defects. The main defects related to surface quality of WEDMed parts include: occurrence of “lines” and “marks”, surface roughness, and recast layer (also called white layer), shown in Figure 43.



Recast layer ‘‘Lines’’ and ‘‘marks’’ Surface roughness

Figure 43: typical defects of wire EDM products

Within the IFaCOM project, a dedicated system has been developed and implemented on a GFAC machine (see Figure 44).

Figure 44: Cut 200 wire EDM machine, platform used for IFACOM GFAC’s demonstrator

The implemented system tackles the elimination of critical surface defects that could arise at some points of the part and could reduce the fatigue resistance to levels not accepted for such applications.
The system develops the IFACOM concept framework at three levels:

- a real-time control of the vital process parameters
  This system relies on high-speed data acquisition and processing of relevant process parameters (current, voltage) and performs the diagnosis of surface defects by detecting abnormal variation of some signal features, like short circuits characteristics.

For testing and setting up this system, several intermediate developments have been necessary for interfacing the machine controller with the IFaCOM system and performing high-speed data acquisition (MHz).
Once the system has been proven efficient, a real integration has been performed including ad hoc software and hardware development (Figure 45) for performing the high-speed process monitoring and control.

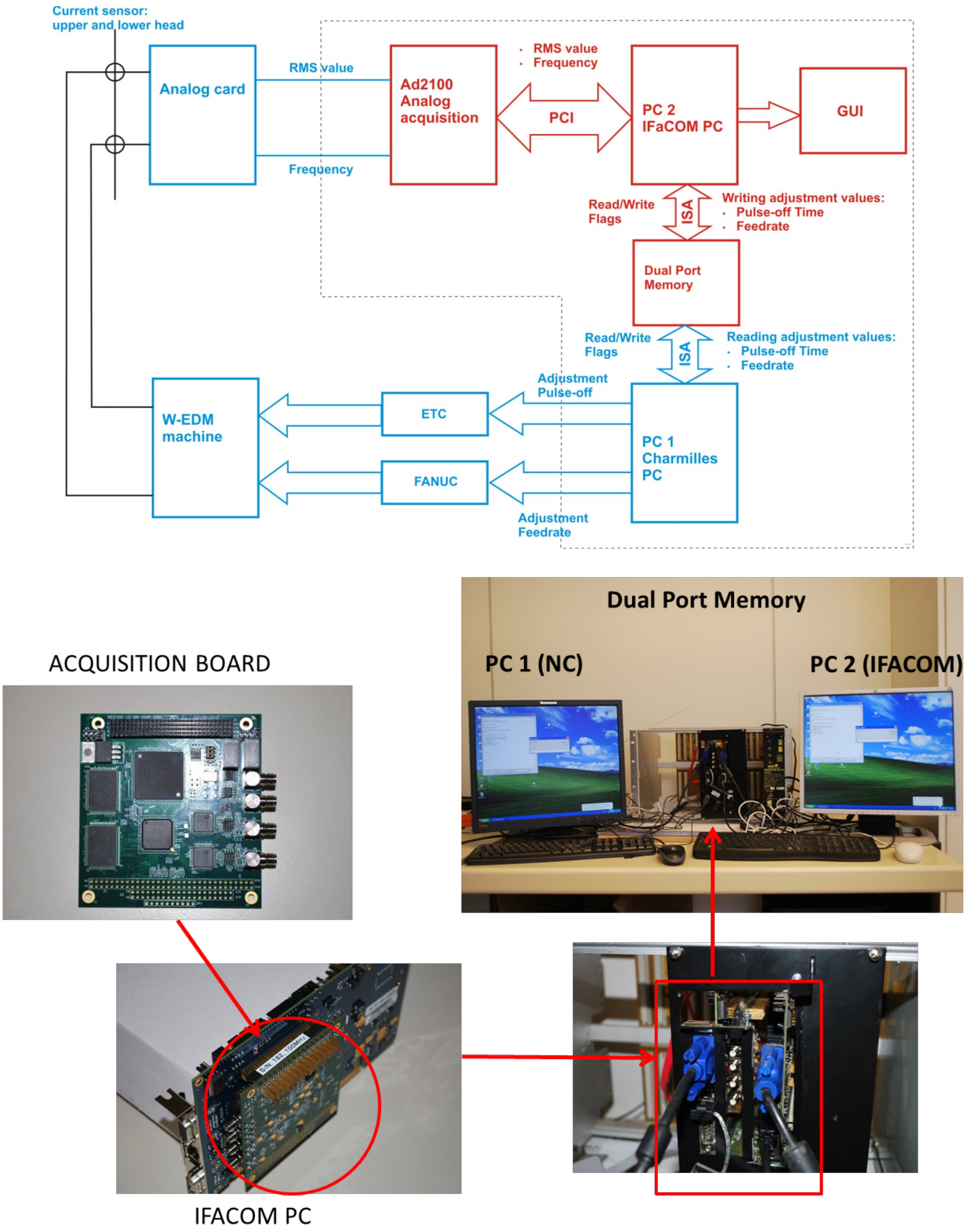
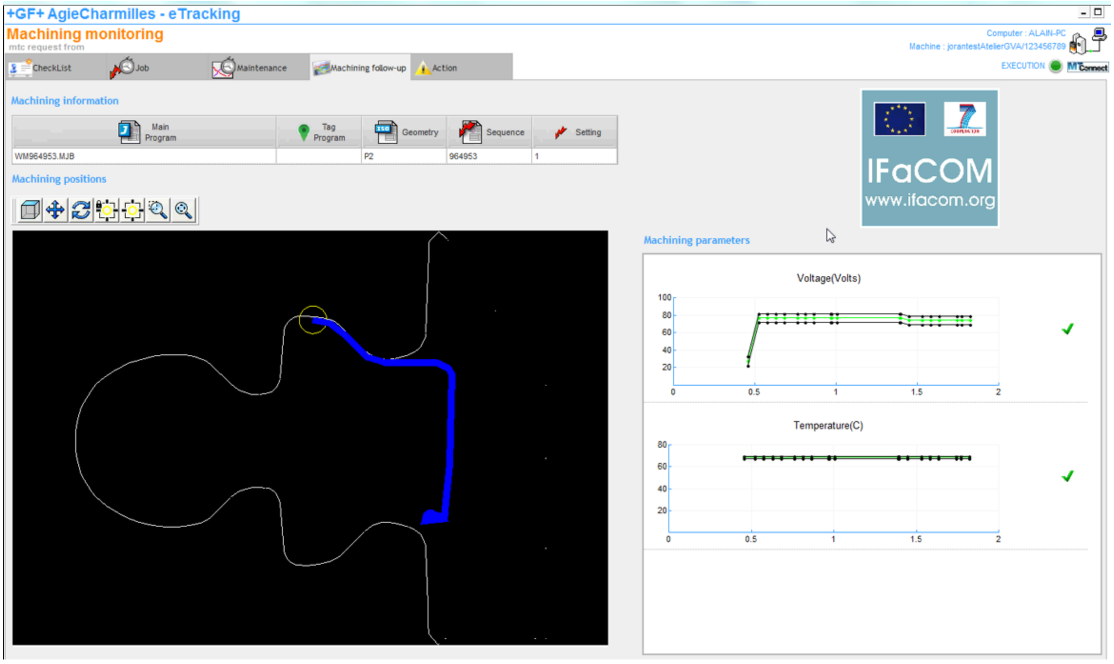


Figure 45: System interface and integration; ad-hoc hardware software developments required for the implementing the real-time IFaCOM control system

- a second monitoring and e-tracking control system.
  This system has been developed within the project for detecting if any critical event has not been corrected by the real-time IFACOM control. In such a case, a machining report

indicates the position where this event occurred, for further inspection or correction. The value of such parameters can be followed in real-time with respect to reference values associated with part quality and position on the machining path (Figure 46).



Computer : ALAIN-PC
Machine : jorantestAtelierGVA/123456789

Main Program	Tag Program	Geometry	Sequence	Setting
WM964953.MJB		P2	964953	1

Figure 46: e-tracking system monitoring and recording of critical process indicators.

- Long-term, off-line correction system
  This system, based on the application of the fuzzy logic approach of WP6, allows to optimise the process towards zero defect based on the level of detected errors at working conditions.

4. Potential impact, main dissemination activities and exploitable results

4.1 Potential Impact

Since the beginning, IFaCOM has focused and prioritised industries and industrial applications.

Throughout the course of the project, the consortium has developed a methodology for the achievement of zero defect manufacturing. The methodology has been proven effective in different industrial scenarios, both in the aerospace and in the machine tool field.

Due to the variety of cases addressed, and to the peculiarities and constraints of each of them, it is difficult to systematically generalize and extend project results to the European machine tool and aerospace industries. In fact, depending on several case-dependent factors (the application, the size of the company, the centrality of the machine/process in their production, the cost of the installed control system, the development stage reached during the project etc.), the impact of the improvements made within the project changes considerably.

Nevertheless, project achievements have been reviewed by each end user and their evaluations show promising trends in terms of

- **Improved quality.** Application of the ad hoc developed equipment has allowed to significantly reduce defects in quantitative (number) and qualitative (entity, dimensions) terms (i.e. reduction of inclusions, EMA)
- **Increased predictability of quality** Increased data availability allows to analyse and predict production's outputs. Also, some developments done within the project (i.e. e-tracking system, GFAC) allow to predict, identify and localize defects, reducing the effort of post process quality controls
- **Increased throughput / productivity.** Process automation, process monitoring and control allow to reduce the time cycle and time consuming side-activities (quality checks, rework, fitting operations) increasing the overall company throughput (i.e. Strecon, GKN)
- **Improved robustness of processes or product.** More stable and repetitive processes reduce the variance of quality results (i.e. GKN, GFAC)
- **Reduced direct human labour costs and expenses.** Automation and intelligent process control leads to a reduced use of manual labour and, consequently, reduced costs (i.e. GKN)
- **Reduced process cost.** Faster and more efficient machines and processes allow to reduce single process cost (less human supervision, manufacturing time reduction, less waste)
- **Reduced material cost.** Quality improvements lead to less scrap parts and less material waste, more predictable tolerances and allow to optimize the design of components reducing material usage (i.e. Alesamonti, reduced manual fitting activities)
- **Reduced quality control cost.** As described previously, online process control costs less than post process control
- **Increased process know how.** Data availability has a direct effect on companies know how on their processes, allowing data analyses and interpretation, better process understanding and possibilities of future improvements
- **Improved data processing / interpretation.** The application of machine learning/artificial intelligence methods allow to derive information on the process and make decisions

otherwise difficult to extrapolate developing and using complex mathematical models (i.e. EMA, GFAC)
- **Better use of human resources.** Process control and automation allow to replace human operators in tasks that involve hard physical or monotonous work (i.e. GKN's TRF bending and welding); workers can take on other roles, typically higher-level jobs running/supervising of the automated processes.
- **Improved product competitiveness in the market**. Intelligent machines and controlled/ certified processes guarantee better quality products and are more appealing for customers.

Also, some minor drawbacks have been identified

- **Increased equipment cost.** The use of additional equipment installed on machines lead to an increase in the equipment and installation costs.
- **Increased maintenance cost.** The use of additional expensive equipment require additional maintenance activities.

As expected, company heading towards an increased process control, automation and a zero defect manufacturing may face a high initial costs in purchasing technology and increase their maintenance costs, but, in the medium-long term, the introduction of new technologies showing all the (economical) advantages listed before, will pay back the initial investment. In fact, projects' end users have a unanimous perception that the introduction of the IFaCOM methodologies and technologies will have a positive financial impact on their companies' gross margin in the medium-long term.

Among industrial players participating to the project, also technology suppliers have highly benefitted from the project results; in fact, they have developed new products or improved existing ones, establishing commercial relationships with new customers and enhancing their offer and their competitiveness on the market.

In order to broaden the impact of the project, several initiatives have been taken, including the formalization of the project best practices, several standardization activities and the clustering 4ZDM initiative, which involves the other 3 ZDM project and aims at integrating projects' results, deriving a common strategy towards zero defect manufacturing.

4.2 Main dissemination and exploitation activities

Dissemination of results has been one of the main goal of all IFaCOM partners.
Therefore, the IFaCOM consortium has created a dissemination plan aimed at maximizing the project impact. The main aim of the awareness and dissemination plan has been to address the following issues:

- To disseminate project results will achieve both to the largest possible concerned audience and to targeted industrial partners such as sensor and control equipment producers, aerospace and machine tool companies, researchers in the field of manufacturing, etc.
- To encourage the use of intelligent signal analysis, fault diagnosis and prognosis methods and implementation of real-time self-correcting mechanisms as well as medium and long-range optimization methods for increasing the part quality level and overall performance and stability of manufacturing systems within the selected industrial branches.

Dissemination has been one of the main targets of WP9, also focused on exploitation. In this WP, all the partners have contributed

- designing a dedicated web-site;
- publishing project results in scientific publications, journals and magazines in the field of sensing and control equipment, machine tool and aerospace production;
- presenting project results in scientific conferences and workshops;

- distributing information material and showing demonstrators to a wide audience during exhibition fairs and through direct communication with relevant interest groups
- promoting education (students) and training (professionals)

The IFaCOM consortium has been very active in the dissemination activities. For example, some of the most important conferences and publications are listed in the next sections.

WP9 has also focused on the exploitation of the project results, maximising the exploitation potential of project results and developing an appropriate methodology and strategy for knowledge management and protection of intellectual property rights.

More details on the project exploitation activities are described in a dedicated document, the Plan for Use and Dissemination of Foreground (PUDF) which describes the

- Dissemination of foreground
- Exploitation of results
- Success factors for exploitation and means to measure their effective impact
- Risks related to their attainment

The main project exploitable results are listed at the end of this document.

4.3 Conferences, Fairs, Workshops

- 11th International Symposium on Measurement Technology and Intelligent Instruments (ISMTII), Aachen, Germany, 01- 05.07.13
- 3rd International Conference on Virtual Machining Process technology (VMPT), Calgary, Canada, 20-23.05.14
- Workshop on Monitoring of Machining Processes, January 31, 2013, Technical University of Denmark, Lyngby, Denmark.
- CIRP STC S “Surfaces” meeting within Part 2 of the CIRP General Assembly, August 22nd 2013, Copenhagen, Denmark.
- Surface Generation Seminar, KTH, Stockholm, 04.06.2014.
- Workshop on Metal Cutting, Technical University of Denmark, Lyngby, Denmark, January 27-28, 2015
- Precision Polymer Processing Research Seminar, Technical University of Denmark, Lyngby, Denmark, 23.10.2014
- 65th CIRP General Assembly, Cape Town, South Africa, 23-29.08.15.
- Workshop J.LEAPT , 24 Nov. 2011, Fraunhofer IWU, Chemnitz, Germany
- 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering – CIRP ICME’14, 18-20 July 2012, Ischia, Italy
- Workshop DICMAPI, University of Naples Federico II, Faculty of Engineering, 7 Jun. 2013, Naples, Italy
- Towards Cyber-Physical Production Systems International Workshop, 11-12 October 2013, Hungarian Academy of Sciences (MTA), Budapest, Hungary
- BIMU Fair 2012, Milano, Italy, 02-06.10.2012
- MECSPE Fair 2014, Parma, Italy, 26-29.03.2014
- 14th Euspen International Conference, Dubrovnik, 02-06.06.14
- BIMU Fair 2014, Milano, Italy, 29.09-04.10.2014
- Seminar on Process monitoring, University of Mondragon, Spain,10-12.06.2014
- MECSPE Fair 2015, Parma, Italy, 25-28.03.2015
- Workshop, Sistemi innovativi per il monitoraggio dei sistemi di produzione, KEYMEC, San Vito al Tagliamento (PN), Italy, 25.01.2013
- Workshop, Fabbrica del futuro, Industria 4.0, Udine, Italy, 27.02.2014
- SMAU Fair, Naples, Italy, December 11-13, 2014
- 15th Euspen International Conference, Leuven, Belgium, 01-05.06.2015
- Conference, Sfide per i materiali nella generazione termica di energia del XXI secolo, AIM - Associazione Italiana di Metallurgia - Milano, Italy, 12-13.11. 2013.

- CIMTEC 2014,13th International Ceramics Congress – Montecatini Terme, Italy, June 8-13, 2014
- Forum for Automatisk Produksjon 2014, 27-28.08.2014 Gjøvik, Norway
- CIRP General Assembly, 24-30 August 2014, Nantes, France
- CIRP January Meeting, January 2015, Paris, France
- Euromold Fair, Frankfurt, Germany, December 3 - 6, 2013
- Cyber-Physical System in Manufacturing and Production workshop, Brussels, 29-30 October 2013
- World Manufacturing Forum 2014, Milano, Italy, 1-2 July 2014
- Imagine FoF 2020, factories of the Future towards 2020 Joint Dissemination Conference, Geneva, Switzerland, 12-14 June 2013
- 16th International Conference on Sensors and Measurement Technology (SENSOR 2013), Nürnberg, Germany, 14-16 May, 2013
- 21st MF HLG meeting in Mannheim, Germany, on 05-11-2013
- Aachener Werkzeugmaschinen Kolloquium, AWK 2014, Aachen, Germany, 22-24.05.2014
- Manufuture 2013, Vilnius, Lithuania, 6-8 October 2013
- GMA Automation conference, Baden-Baden, Germany,June 2015
- 5th CATS 2014 - CIRP Conference on Assembly Technologies and Systems, Dresden, Germany 12-14.11.2014
- International Conference on Intelligent and Automation Systems (ICIAS 2013 Intelligent Fault Correction and self Optimizing Manufacturing Systems, Hanoi, Vietnam 23-24.02.2013
- SyRoCo 2012, Dubrovnik, Croatia, 5-7 September 2012
- Quality Bridge Convention, BIMU 2014, Milano, Italy 29.09-04.10.2014

4.4 List of Publications

- Malagola G., 'Da SOMMACT a IFaCOM: verso lo Zero-defect manufacturing', INNOVARE magazine - Issue 3/2013, April 2013
- Meier N., Georgiadis A., "Optical Part Measuring inside a Milling Machine", Key Engineering Materials, Vol. 613, pp. 440-445, May. 2014
- Arif M, Xirouchakis P, Ahmed B, Olcay A, Nenad N, Robert P, Stucki M. A generic system architecture for simulation based intelligent multi-stage multi-process machining system to achieve zero-defect manufacturing. International Conference on Sustainable Design and Manufacturing (SDM), Cardiff, United Kingdom, April 28-30, 2014
- Morand M.P. , Master Thesis, "Experimental investigation of surface integrity and defects for a quality assurance system of WEDMed aerospace parts", EPFL, 2014
- Ferretti, S., Caputo, D., Penza, M., D'Addona, D.M., 2012, Strategies for Zero Defect Manufacturing: an Overview, 8th CIRP Int. Conference on Intelligent Computation in Manufacturing Engineering – CIRP ICME '12, 18-20 July, Ischia, Italy.
- Di Foggia, M., D'Addona, D.M., 2012, Identification of Critical Key Parameters and their Impact to Zero-defect Manufacturing in the Investment Casting Process, 8th CIRP Int. Conference on Intelligent Computation in Manufacturing Engineering – CIRP ICME '12, 18-20 July, Ischia, Italy, Elsevier Procedia CIRP, ISSN: 2212-8271
- C. Caramiello, S. Iannuzzi, A. Acernese, D.M. D'Addona, A mixed SVD-neural network approach to optimal control of ceramic mould manufacturing in lost wax cast processes, Advances in Science and Technology Vol. 87 (2014) pp. 105-112, 2014
- Schmitt R., Wiederhold M., 'Wirtschaftliche Absicherung von Prüfentscheiden' in: ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb 109 (2014), 4, ISSN 0947-0085, S. 197-199
- R. Schmitt, M. Wiederhold, J. Damm, M. Harding, P. Jatzkowski, R. Ottone, "Cost-Efficient Measurement System Analysis for Small-Batch Production", Key Engineering Materials, Vol. 613, pp. 417-427, May. 2014
- R. Schmitt, H. Bosse, Measurement Technology and Intelligent Instruments XI, in Key Engineering Materials, Volume 613 May 2014
- Pilný L, Bissacco G, De Chiffre L, Ramsing J, 2013, 'Acoustic Emission Based In-process Monitoring in Robot Assisted Polishing' In: Proceedings of the 11th International Symposium

- on Measurement Technology and Intelligent Instruments (ISMTII), Aachen, Germany, 01-05.07.13
- Pilný L, Bissacco G, De Chiffre L , 2014, 'Validation of in-line surface characterization by light scattering in Robot Assisted Polishing', In: Proceedings of the 3rd International Conference on Virtual Machining Process technology (VMPT), Calgary, Canada, 20-23.05.14
- Pilný L, Bissacco G, De Chiffre L, 2014, 'The effect of scattered light sensor orientation on roughness measurement of curved polished surfaces', In: Proceedings of the 14th Euspen International Conference, Dubrovnik, 02-06.06.14, vol. 1, pp.233–236.
- Pilný L., Dalla Costa G., Bissacco G., De Chiffre L., 2015, Development of a multisensory arm for process monitoring in Robot Assisted Polishing, In: Proceedings of the 15th Euspen International Conference, Leuven, Belgium, 01-05.06.15.
- Pilný L, Bissacco G, De Chiffre L, Ramsing J, 2015, 'Acoustic Emission Based In-process Monitoring in Robot Assisted Polishing', International Journal of Computer Integrated Manufacturing, DOI: 10.1080/0951192X.2015.1034180
- Pilný L., Bissacco G., 2015, 'Development of on the machine process monitoring and control strategy in Robot Assisted Polishing', CIRP Annals Manufacturing Technology, Vol. 64-1
- Pilný L, 2015, 'Process monitoring for intelligent manufacturing processes — Methodology and application to Robot Assisted Polishing', PhD thesis, Department of mechanical engineering, Technical University of Denmark.
- Tingelstad L., Egeland O., Robotic assembly of aircraft engine components using a closed-loop alignment process, In Procedia of the 5th CATS 2014 - CIRP Conference on Assembly Technologies and Systems, Volume 23, pp 110–115
- Tingelstad L., Capellán Azofra A. J., Thomessen T., Lien T. K., Multi-Robot Assembly of High-Performance Aerospace Components. Elsevier IFAC Publications / IFAC Proceedings series. vol. 10 (1) (2012)
- De Agustina B, Marín MM, Teti R, Rubio EM. Surface Roughness Evaluation Based on Acoustic Emission Signals in Robot Assisted Polishing. Sensors. 2014; 14(11):21514-21522.
- Myklebust O., Zero Defect Manufacturing: A Product and Plant Oriented Lifecycle Approach, Procedia CIRP 01/2013; 12:246-251

4.5 Key Exploitable Results

The Key Exploitable Result of the project is a working methodology, resulting from the combination of the research and developments results. The exploitable results (33) achieved during the project are shortlisted below:

- Numerical Control integrating and interfacing IFaCOM advanced sensor systems
- Insert cutters wear monitoring for torical milling tools
- Measurement solutions for parts thickness
- An improved method for calibrating vibration sensor
- Real-time control of Robotic Automating Process / sensors, SW, robot control
- Measurement and quasi real-time compensation of machine tool geometric errors
- SPC for small and single batch production
- Apparatus and method to minimize large parts deformations due to clamping
- Development of hardware system solutions for closed loop analysis and controlling of manufacturing process parameters in real-time
- Uniform and controlled slurry making processing using advanced monitoring solutions
- Method for tool change in automatic RAP
- Method for in-process detection of stabilization of surface generation in RAP
- Sensorized arm for Robot Assisted Polishing
- Method for on the machine total surface characterization and process validation
- Method for on the machine surface defects detection and location recording
- Efficient validation of many measurement processes/validation of complex measurement processes
- Development of two guidelines for the efficient proof of capability of (1) many and (2) complex measurement processes
- Artificial Neural Network method for slurry control and optimization
- Vision and force control: Improved methods in assembly

- Automatic assembly, tack welding, full seam welding of jet engine Turbine Rear Frame
- Generic algorithm for selecting best fitting parts for an assembly
- Online defect detection and process adjustment method and software for WEDM
- Human-Machine interface and ActiveMQ Message broker for machine event monitoring-integration: consulting and customized development
- Highly modularized software architecture
- Tool change and crash detection in a RAP machine based on relative regression models.
- Optical part measuring inside a milling machine
- A Fuzzy-net based method for online adjustment suggestions for of vital process parameter(s) to prevent part quality defects
- Application of the Fuzzy-nets based method and software for process parameters adjustments in WEDM
- e-tracking software for zero-defect surface quality assurance system
- 3D volumetric compensation algorithms for zero-defect manufacturing
- Application of XRF method to measure the silica content in ceramic slurry
- Robot programming method for robot vison control in assembly and tack welding
- Signal processing algorithms for sensor fusion feature extraction on Wire EDM voltage and current signals.

5. Contact Details for the IFaCOM Consortium

IFaCOM Project website: http://www.ifacom.eu

Project Coordinator: Mr. Odd Myklebust (odd.myklebust@ntnu.no)
University: NTNU

Partners in the project:

NTNU – Trondheim
Norwegian University of
Science and Technology

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

WZL
RWTHAACHEN

DTU

LEUPHANA
Institut für Produkt-
und Prozessinnovation

VOLVO AERO

EMA

+GF+ AgieCharmilles

alesamonti
efficiency + innovation

CADCAMation SA

INOSENS
innovation in sensorik

STRECON

Montronix®

FIDIA