POLITECNICO DI MILANO

PhD Yearbook | 2008

# MANUFACTURING AND PRODUCTION SYSTEMS

# Index

Chair:
**Prof. Bianca Maria Colosimo**

# DOCTORAL PROGRAM IN MANUFACTURING AND PRODUCTION SYSTEMS

Manufacturing is a leading sector of the European economy since European Manufacturing is a dominant force in international trade. As an example, the EU's share of total global manufacturing trade was 18% in 2004, while the US had 12% and Japan 8%. (Manu*future* Strategic research Agenda – September 2006 – European Commission).
In some key sectors such as machine-tool, robot, and automation industry, Italy has even achieved a global leadership, accounting for about 10% of the total export (acting as the third in the world) and Lombardia is playing a dominant role, hosting 48.2% of the Italian companies (Report 2005 of the *Association of Italian Manufacturers of Machine Tools, Robots, Automation Systems – Ucimu*).
In this competitive scenario, Politecnico di Milano has the fundamental role of providing people with specific training in Manufacturing and Production Systems engineering, by strengthening their research skills in the industrial and academic context. Therefore, the PhD programme in Manufacturing and Production Systems focuses on the optimal transformation of raw materials into final products, addressing all the issues related with the introduction, usage, and evolution of technologies and production systems, during the entire product life cycle.

The professional skills acquired in the degree program give the competence for managing and solving problems related with product and/or service realization. In particular, issues of continuous improvement and integration of all the activities ranging from conception to realization are emphasized.
A PhD in Manufacturing and Production Systems acquires her/his knowledge through the activities of study, research, lab experience, development in cooperation with industries, foreign institutions and international research groups. Using her/his background, the PhD candidate will be able to blend the exactness of scientific knowledge with the ability to deal with practical industrial problems. The outlined skills are of great interest to industrial companies devoted to: i) continuous improvement of technologies and processes; ii) strong integration of product-process-system design; iii) complete product lifecycle management; iv) optimal design of production, logistic and service systems. In this view, a PhD in Manufacturing and Production systems can eventually aim at prestigious positions at national and international level within industrial companies, consulting companies, universities and research institutions.

PhD activities can specifically focus on one of the following topics:

- Manufacturing Processes: This research area is aimed at studying both conventional and innovative manufacturing processes. The study can specifically deal with: developing new processes for innovative applications or for innovative materials; evaluating the application constraints of new and existing manufacturing processes; performing economic optimization of the process performances; investigating on the relationship between process parameters and process results. The research area is therefore very wide, with activities ranging from basic to industrial research.
- Production Systems: The research activities carried out in this area are concerned with the design and management of integrated production systems. The research activities encompass innovative and traditional system architectures in different sectors (machine tools manufacturing, production of mechanical components, services). Studies and research activities are based on real cases and underline the deep relations amongst products, processes and production systems.
- Quality in Manufacturing: Quality has a relevant role in the new competitive scenario in which European manufacturing is pushed toward high-value products. Research activities in this area focus on studying and developing new approaches, methods and tools for quality management, process monitoring, control and optimization and metrological issues (design and verification of geometric product specifications).
- Product Lifecycle Management (PLM): This area provides the methodologies and tools related to computer-based product lifecycle management, with emphasis on the automation and integration of product design and process planning.

Relevance is also given to the impact of process design on production-system design, both at single-plant level and at network-enterprise level.

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# HIGH PERFORMANCE SPINDLE DESIGN METHODOLOGIES FOR HIGH SPEED MACHINING

**Paolo Albertelli**

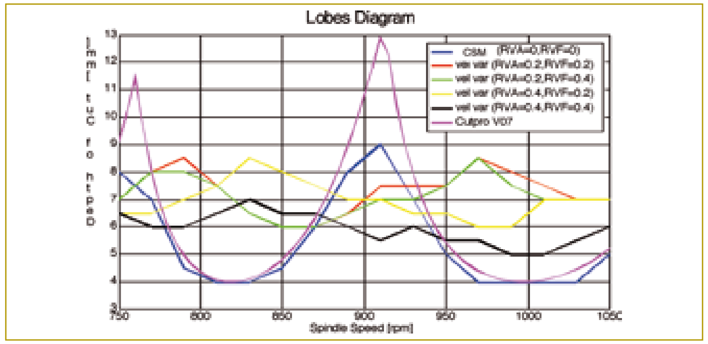
In this thesis the research efforts have been focused mainly on spindle system performance improvement especially for High Speed Machining applications. Different design solutions and strategies have been analyzed and developed in order to increase the Material Removal Rate and to obtain better workpiece surface quality.
In High Speed Machining the most important limiting factor is the occurrence of the cutting process instability usually called chatter instability. Frequently this phenomenon is strictly related to the spindle dynamic behaviour so a methodology to model and deeply comprehend the spindle system has been proposed. An intensive experimental activity was performed in order to update the proposed spindle structural models, [Fig. 1]
These experimental modal tests, planned on different spindle setups, have allowed to characterize and to evaluate the properties of some important spindle components that contribute to the overall spindle dynamics.
The results of these activities consist of a set of modelling guidelines useful to build reliable spindle models. These modelling methodologies and the linked updating tips can be used to easily test innovative design solutions. The design of a carbon fiber-epoxy composite material spindle shaft has been presented as a concrete example. Considering the hypotheses introduced in the proposed analysis; the use of the designed composite shaft seems not particularly promising if the MRR improvement is considered as the most important target.
Moreover, the dynamic interaction between the spindle system and the machine tool has been studied in this thesis. Two different modelling approaches to evaluate the influence of the machine structure on the dynamic behaviour of the spindle have been proposed. The first one is particularly suitable for spindle designers while the second one can be more easily adopted by the machine-tool producers. The analysis and the experimental tests performed on different industrial cases reveal the strong interaction between the two components especially considering the frequencies involved in high speed machining. It is therefore more important to consider these aspects during the spindle design to correctly estimate the stability lobes diagram and to optimize the spindle design.
Moreover, in this thesis the Spindle Speed Variation technique has been studied as a promising chatter suppression method. Particular attention has been focused on the deep comprehension of the

**1. Experimental modal analysis on spindle assembly**

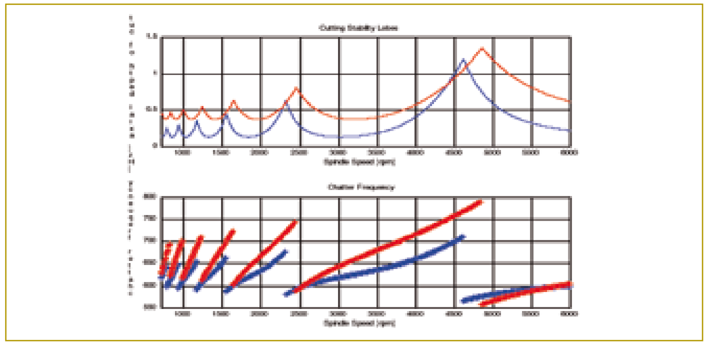
complex effects of the speed modulation on the regenerative phenomenon. The instantaneous chip thickness modulation that strictly depends on the Sinusoidal SSV parameters has found to be the key factor for the effectiveness of the technique. An energetic analysis has been proposed to properly select the main SSSV parameters. More precisely, the parameters (RVA,RVF) selection is based on the minimization of the reported functional that is strictly related to the energy introduced in the machine tool system by the cutting process:

$$\begin{cases}\max\limits_{RVA,RVF}\left(J=\int_{t}^{t+T}\left(\left|\Phi(t\,|\,RVA,RVF)-\Phi_{worst}\right|\right)dt\right)\\ s.t.:\ \underline{a}<RVA<\overline{a},\ \underline{b}<RVF<\overline{b}\\ \forall\Omega_0\in[\Omega_{inf};\Omega_{sup}]\end{cases}$$

The reliability of the proposed fast approach has been checked comparing the results obtained by time domain simulations.




**2. Lobes diagram, Spindle Speed Variation**



**3. Stability diagram, active vibration control enhancements**

The SSSV seems to be very effective in chatter vibration reduction especially for low speed machining; in these regions of the stability chart the right selection of the modulating parameters is less critical than in high speed machining and therefore the technique shows an important robustness, [Fig. 2]. An experimental cutting test campaign would be necessary to strengthen the results obtained via time domain simulations.
Active vibration damping strategies have been analyzed as chatter suppression technique. An application to an active spindle system with four piezo actuators has been developed. A model based control strategy (LQG) has been proposed in order to control tool tip displacement and thus to improve the quality of the machined surfaces. Relevant enhancements in cutting stability were observed from simulated results: the asymptotical stability limit was almost doubled, [Fig. 3]. An additional control strategy based on the cutting force prediction has been designed in order to reduce the tool deflection occurred during the machining. A first stage of experimental tests has been performed in order to verify the damping properties provided by the control action.

# AUTOMATIC CONTROL OF THE LASER HARDENING PROCESS BY MEANS OF SCANNING TEMPERATURE MEASUREMENTS

**Moreno Castelnuovo**

Laser hardening (LH) is a process well suited to improve wear and fatigue resistance of mechanical parts made by steel and iron. In most cases, the wear resistance obtained with LH is higher than that obtainable with other competing heat treatment processes (e.g. induction heating), and repeatability is higher too. But what is of major importance is that thermal distortions of processed components are limited due to the very low heat input, therefore limiting, or even avoiding, re-working of the part (e.g. grinding). The self quenching effect, typical of this process, eliminates the need for a quenching step in the manufacturing sequence. These reasons lead to both manufacturing costs reduction and higher quality of treated layers. This is particularly true since the developments of high power diode lasers.
Despite LH is a very attractive process, its use in industry is still limited. This is mainly due to high capital costs, the need for skilled operators, and the need for some extra equipment for measuring and controlling the temperature of the heated surface. In fact, one of the most critical point of the LH process is its sensibility to process disturbances such as surface irregularities and geometry variations of the work-piece.

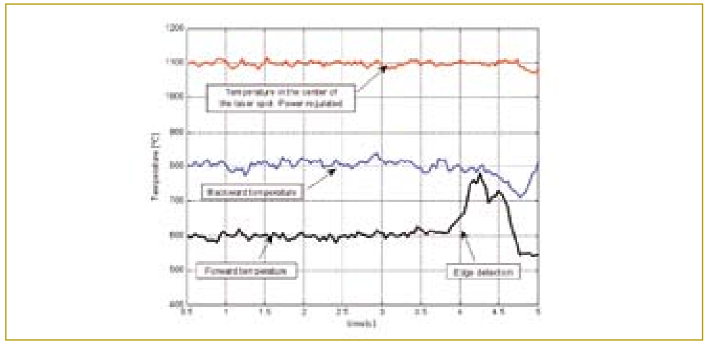
When working at constant parameters, the occurrence of a disturbance can lead to the melting of the surface with the consequent rejection of the processed part. To avoid this eventuality the temperature at the surface must be controlled. Unfortunately with the power regulation it is only possible to keep the surface temperature at a constant value, but the constancy of treated thickness is not always guarantee. In fact, even maintaining the maximum temperature constant, a change in the geometry of the work-piece (e.g. thickness variation, edges) can produce a deep modification of the three-dimensional temperature field at the surface, then into the bulk material, leading to a poor quality of the treated layer. In order to obtain a constant treated layer it is possible to regulate some other machining parameter (e.g. scanning speed of the laser beam). Thus, the research was aimed to find a final solution to the problem by the development of a new strategy for measuring and controlling the laser hardening process by the multivariable regulation of process parameters in order to produce a treated layer of both mechanical and geometrical constant characteristics.
Due to the poor spread of laser hardening into modern industries, instruments for temperature measurements during the machining are generally overqualified or require some upgrades to accomplish their job. Thus, during the first phase of the research a pyrometer was designed and realized expressly for the laser hardening process. Then, to get more insights about the way the thermal field changes as a function of geometrical disturbances it was necessary to develop a new instrument capable of measuring the temperature along the direction of the moving beam. For this purpose a scanning pyrometer was realized. In particular the movement of the measuring spot along the travelling direction of the beam was obtained by coupling the afore designed pyrometer and a galvanometer [Fig. 1].
Then, on the basis of experimental results it was possible to define an

1. The designed scanning pyrometer

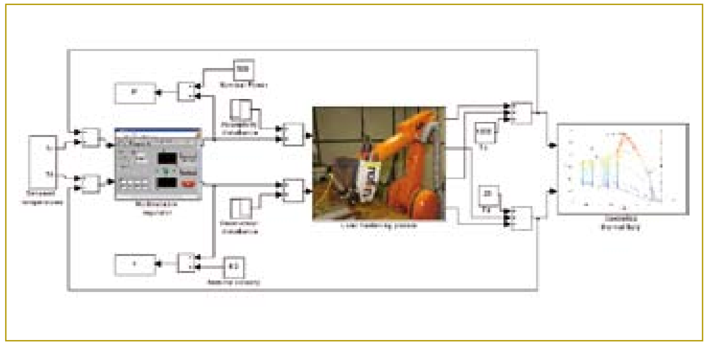









2. Scanning temperature measurements for the detection of geometrical disturbances



3. Layout of the multivariable control system of the laser hardening process

intelligent way to look at the thermal field in view of the multivariable control. Eventually a multivariable regulator was designed to control the thermal field with the aim of maintaining the three-dimensional thermal field as constant as possible thus leading to the achievement of a treated layer of high quality.
Using an automatic power regulation it is possible to keep the maximum temperature in the center of the laser beam at a constant level. Then, it was found by means of scanning measurements, that the only way to identify a geometrical variation is by monitoring the temperature both in front and behind the laser beam [Fig. 2].

This approach has a general validity inasmuch is capable to identify several kinds of geometrical disturbances.

Besides, condensing the information linked to the forward and the backward temperature in one control variable it is possible to improve the extent of the control on the laser hardening process. In particular it was demonstrated that regulating the power and the scanning speed of the laser beam [Fig. 3] it is possible to control the temperature of the surface at least in three point leading to a good control of the thermal field. In the final analysis a multivariable control of the laser hardening process along with a multiple temperature measurements can lead to a treated layer of high quality in terms of geometrical and mechanical properties.

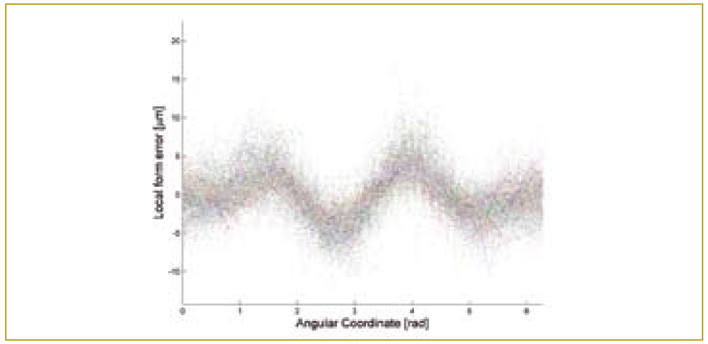
# GEOMETRIC TOLERANCES VERIFICATION: STRATEGY OPTIMIZATION FOR CMM MEASUREMENT

**Stefano Petrò**

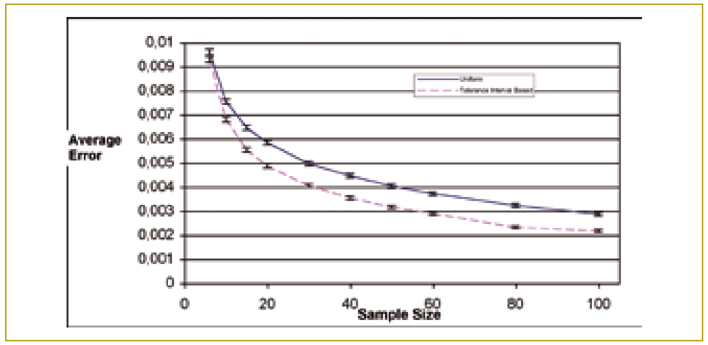
The demand for high quality products is increasing. Superior performances are more and more often required by the market, and these performances are not required only to high-end products, but to mass production, too. Therefore, techniques able to solve the problem of economically ensure the good quality of large scale production have to be proposed. In particular, in the fields of mechanics final products are usually constituted by several parts which fit together.
To ensure correct fitting, "tolerances" are stated for parts constituting the final product. Three kind of tolerances are usually considered: roughness tolerances (which mainly regard the surface finish of part), size tolerances (describing the admissible deviation from the nominal extent), and geometric tolerances (stating how much a part can deviate form its nominal shape). If for simple fitting the definition and check of roughness and size tolerances are usually sufficient, for complex fittings, geometric tolerances are required.
For the verification of size tolerances simple instruments (gauges, micrometer,…) are usually sufficient, but to check geometric tolerances more complex measurements are required. To apply ISO 1101 international standard definitions of geometric tolerances, clouds of points have to be sampled on the surface of parts under inspection; then, an ideal "substitute geometry" is fitted on clouds, and maximum deviation of sampling points from the fitted geometry is taken as evaluation of the geometric error: if geometric error is lower than the geometric tolerance, then the part is conforming. A measuring instrument usually adopted to verify geometric tolerance is a "Coordinate Measuring Machine" (CMM).
Two sources of costs may be identified in the verification process. Of course, performing the required sampling requires an expense; this "measurement cost" is usually proportional to the number of sampling points taken. Then, because a measurement error is always present, an "errors cost" related to inspection errors (e.g. stating a conforming part is not conforming) arises. Unfortunately, measurements uncertainty, which quantifies the average measurement error, is inversely proportional to sample size, so, in order to minimize the overall inspection costs a trade off between measurement costs and errors cost has to be identified. The aim of this work is therefore to find the cost optimal sampling strategy.
A sampling strategy essentially defines the sample size, and the sampling points pattern. If increasing the sample size always tends to reduce uncertainty, an optimal sampling points pattern may further reduce uncertainty. But how can pattern be planned?
The "manufacturing signature" may come in aid to this aim. The geometric error that may be found on mechanical parts is usually constituted by a random part, and a repeatable part. The random part is due to the presence of dirt, vibrations, non homogeneous material, and similar random factors during production; the repeatable part of the geometric error is due to the production process itself: no "perfect" production process exists, therefore every production process will leave on manufactured parts its fingerprints (e.g. roundness profiles of turned shafts usually show lobing [Fig. 1]). This repeatable part of the form error is called the "manufacturing signature" of the process.
Because presently the evaluation and verification of geometric tolerances considers only the maximum deviation from the nominal shape, the knowledge of the signature may help in the identification of those areas of the surface which most often show the maximum geometric error: these area have to be densely inspected.



In order to identify these areas and to place sampling points in them, "Regression Tolerance Intervals" have been applied. Because the amplitude of tolerance interval is locally related to the concentration of sampling points, while the overall amplitude (maximum of the upper limit of the interval minus minimum of the lower limit) depends both on maxima and minima of the average behavior of the signature and on noise superimposed on it, the search of the minimization of the overall amplitude leads to an optimal sampling strategy, with an higher concentration of sampling points in areas the most deviating from the nominal behavior, concentration which is inversely proportional to noise.
Having chosen the optimal sampling points location by means of the Tolerance Interval Based criterion, and found the link between the sample size and the measurement uncertainty, in order to choose the right sample size (i.e. how many sampling points have to be taken), an economical criterion has been proposed.
To consider the presence of measurement error, and simultaneously to guarantee no non conforming part is declared conforming, the ISO 14253-1 standard states that a part can be considered conforming only if it measured geometric error is lower than the geometric tolerance minus the extended measurement uncertainty. This leads to discard conforming parts. The overall inspection cost is therefore evaluated by a measurement cost contribution linearly proportional to sample size, plus an errors cost given by the part value times the expected fraction of rejected conforming parts.
The application of Tolerance Interval Based strategy has lead to a reduction of measurement uncertainty of about the 20-30% [Fig. 2] with respect to a standard, uniform sampling strategy (same sample size).
The application of a signature based sampling strategy is of particular importance in a shop floor environment, where, due to the use of touch trigger CMMs, which are characterized by quite slow sampling rate, the reduction of sample size with good accuracy anyway may lead to significant inspection cost reduction.
Then, the application of the cost function may give an easy way to definitely state the sampling strategy, without the need of an expert intervention.




**1. Manufacturing signature of turned circular profiles**




**2. Measurement error reduction by means of Tolerance Interval Based strategy**

# ROBUST PRODUCTION PLANNING IN MANUFACTURING-TO-ORDER SYSTEMS: A STOCHASTIC PROGRAMMING APPROACH

**Marcello Urgo**

### Project Scheduling Approach to Production Planning

Production Planning is beyond any doubt a complex task. The production plan must define the schedule of the activities to perform, the detailed flow of materials and the utilization of production resources. Production Planning is beyond any doubt a complex task. The production plan must define the schedule of the activities to perform, the detailed flow of materials and the utilization of production resources.

To reduce the complexity of the planning problem, distinct production operations are incorporated into aggregate activities. However, when complex items are produced in Manufacturing-to-Order systems, the duration of aggregate activities can be large. Routings, resource allocation and scheduling of activities must be considered at the production planning level in order to assure feasibility at the detailed scheduling level. A project scheduling approach is in such cases suitable to model the planning problem.

When activities are manually processed by workers, the committed effort can vary over time causing either the resource used in each time period, or the duration of the activity not to be univocally defined. To address this issue, the Variable Intensity Activities formulation of the Resource Constrained Project Scheduling Problem can be used. In this formulation an intensity variable is introduced for each activity to define the effort dedicated to process the activity in each time period. Continuously divisible resources are therefore allocated to activities in quantities varying over time.

### Robust Production Planning

Despite the manufacturing environments are in great part characterized by uncertainty, most production planning approaches assume perfect information and a static deterministic environment. The occurrence of uncertain events can however have a significant impact on the stability and the performance of the production system by affecting the meeting of due-dates, the efficient resource allocation and the usage of non-regular working force. Unexpected events can stem from a number of possible sources: duration of activities, availability of production resources, delivery of raw materials, insertion of new activities, modifications of release times or due dates.

A challenging issue in production planning is therefore trying to design an approach able at incorporating information about uncertainty affecting the schedule and, at the same time, at providing a way to react at the occurrence of uncertain events to preserve the performance of the plan, i.e. a robust production planning approach.

Stochastic programming includes information about uncertainty in the future in a way it is functional to producing a plan that both already considers uncertainty and forecast reactions to uncertainty outcomes and their impact on the plan performance.

To apply stochastic programming to a production planning problem, first-stage variables are used to define the baseline production plan providing a detailed schedule of the activities and the related resources allocation. Second-stage variables are used to represent revisions of the baseline production plan to be enforced after the occurrence of uncertain events.

A set of activities *A* is considered to be scheduled over a time horizon divided into *T* time buckets. Each activity *j* is characterized by a release date $r_j$ and a due date $d_j$. The activities are processed using a set of resources *R*. The percentage of each activity *j* that it is possible to execute in each time bucket *t* must belong to the interval $[b_j, B_j]$. The uncertain events are modeled through a set *S* of scenarios. An occurrence probability $\pi_s$ and a set of activities affected by uncertainty $U_s$ are associated to each scenario *s*.

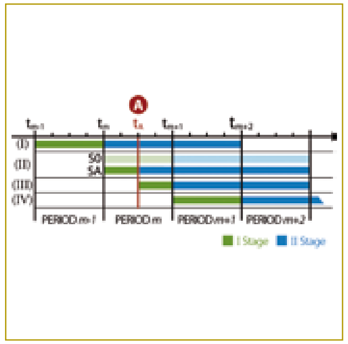
To consider the influence of each different scenario *s*, the objective function aims at minimizing the expected value of the tardiness. Being a sequential decision process, production planning can be naturally modeled as a multi-stage decision process. Unfortunately a complete formulation of the whole multi-stage decision process is likely to be computationally intractable. However, in real manufacturing environments, the influence of far away uncertain events is normally low.

Since the production plan is periodically revised, it could be reasonable to avoid considering uncertain events which are far away in the future. According to this idea, the planning horizon can be narrowed to allow a simpler mathematical formulation and a tractable computational complexity

A two-stage stochastic model can be applied dynamically considering each time only a certain number of consecutive planning periods.

An example of the application of the proposed approach is given [Fig. 1]. Two different scenarios are considered. In the base scenario (*S0*) no uncertain event is supposed to occur while in the scenario *SA* an uncertain event *A* occurs at time $t_A$. The two-stage model is solved sequentially considering a planning horizon of three planning periods.

The model is first solved at time $t_{m-1}$ (I). Since no uncertain event is supposed to occur in period *m*, only the scenario *S0* is evaluated. The first stage schedule covers the whole period *m-1*. The second stage instead begins at time $t_m$ when a new period starts and a new production plan is supposed to be devised. At time $t_m$ the model is solved again (II) considering the two scenarios *S0* and *SA*. The occurrence of different scenarios affects the range of application of the first and the second stage variables. If no uncertain event occurs, the behavior of the model is the same as in application (I). If the scenario *SA* is considered, the first stage ranges from $t_m$ until $t_A$ when the uncertain event *A* happens. The second stage ranges from $t_A$ until the end of the considered horizon.




1. Rolling Horizon Approach

2. MCM Machining Center

### Application to an Industrial Case

To demonstrate the viability of the proposed approach, an application example based on a real manufacturing plant producing machining centers has been carried out. The application to the industrial case has been carried out in collaboration with MCM Spa, an italian company producing machining centers [Fig. 2].

Machining centers and their ancillary equipment must be fabricated, assembled and tested. A detailed model of the fabrication, assembling and testing operations has been compiled, and then aggregated into larger activities. Suitable feeding precedence constraints are used to model overlapping among activities grounding on their percentage execution. The scenarios have been created on the basis of the real available data considering uncertainties affecting the amount of resources needed in the assembling and cabling activities.

The effectiveness of the two-stage stochastic programming approach have been tested through a preliminary campaign to plan the production of a single machining center with some production activities affected by uncertainty. The campaign showed a reduction of the tardiness between 5% and 18% respect to an approach grounding on expected values.

The rolling horizon approach has been tested to plan the production of a set of job orders to be produced within an horizon of about 12 months. The test showed significant benefits in using a stochastic approach against expected value estimation of the uncertain variables.

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