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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MICRODRILLING OF TITANIUM WITH PULSED FIBER LASER: CHARACTERISATION OF THE PROCESS AND REDUCTION OF SPATTER

Carlo Alberto Biffi

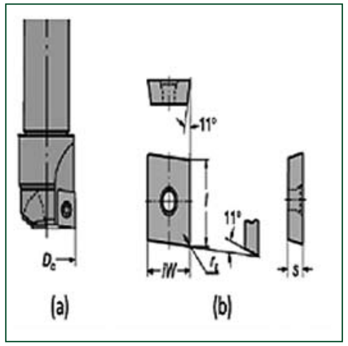
Nowadays a great number of products in several industrial fields are machined by means of laser micromachining processes. Stents for biomedical applications, injection nozzles for automotive field and the machining of silicon to perform integrated circuits are only some of the most interesting examples. For all the industrial applications, the processes must be cost effective, have short enough processing cycle time and they can achieve good quality. In addition, the process must be reliable, controllable and robust.
Laser material processing has demonstrated a very wide ranges of spatial resolutions and high quality of the results in a lot of applications. When the spatial resolution goes to less than 10 microns and sub-microns, many more potential opportunities open up to laser material processing. In particular, laser micro/nano material processing are a powerful and versatile technology for the realization of micro/nano technologies when the practical challenges are overcome.
In combination with these trends, innovative laser sources are developed in order to solve some of the reported problems and to win some challenges. Fiber lasers are the most interesting answer to the previous challenges. Their successfully introduction in a lot of industrial cases in few years is the demonstration that the positive features of fiber lasers are actually appreciated in industrial world. The fiber laser peculiarity is the high efficiency generation of the laser beam directly inside a fiber, which is doped with rare earth elements. This fact allows firstly the laser beam to have a very high beam quality, which influences the results of the material processing. As continuos wave (CW) fiber lasers are already a real opportunity in industrial applications for macro material processing, pulse wave (PW) fiber lasers are the evolution of CW laser sources and they need to be investigated in order to be applied in industrial laser micromachining processes.
In fact, the aim of the present work is to investigate the application of an innovative laser source, which is an IPG 50 W pulsed fiber laser, in laser microdrilling of titanium, which is a very appreciated material in some industrial fields, such as aerospace and biomedical field but it is an hard to machine material by means of traditional processes, most of all when small features have to be performed.
In this work firstly the characterisation of the pulsed fiber laser source is studied and calibration curves between the process parameters, controlled by the laser source, and the main features which define laser pulse are presented. In particular, average power, peak power, pulse energy and pulse width are investigated in relationship with the process parameters (i.e. pump current and pulse frequency). Afterwards, a particular zone of the process parameters is defined, in which the performances of laser pulses in energetic terms do not decrease if pulse frequency increases. This zone in the plain of the process parameters is called "technological zone" because it looks to be very attractive to perform laser micromachining when the maximum pulse energy is available.
Secondly, percussion laser microdrilling, in which a train of laser pulses heats, melts and vaporizes the material to remove, on commercially pure (C.P.) titanium is investigated. The effect of the main process parameters on through hole quality features (diameters, aspects, area of top spatter) is studied. A statistical approach is used to perform the investigations and regressive models are proposed. Besides, drilling time, which is the requested time used to perform a through hole with the best cilindricity, is identified and measured by means a

couple of fast photodiodes. From the measurements, the investigated pulsed fiber laser allows through holes on 0.5 mm thick titanium sheets to be performed in a very short time (2-5 millisecond about). All the performed holes are characterized by a great amount of spatter and melted material in the entrance zone, due to the pulse width in nanosecond order, while exit zone of the holes is free of spatter. Due to the performed holes in several micron dimension, the problem related to the characterisation of the hole dimension and quality is studied and solved. Entrance diameters range from 45 micron to 60 micron, while exit diameters range from 20 micron to 45 micron and they are influenced by pump current, which is the energetic process parameter. The hole aspect, which represents the hole circularity, is enough high and it is not influenced by the investigated process parameters but the high beam quality should be the most influent factor. Due to the presence of spatter, the area of spatter in the entrance zone of the holes is measured and it is demonstrated that it is influenced by both pump current and pulse frequency. Then, some hole transversal sections are proposed in order to characterise the inner wall of the holes, which is regular and cylinder except the entrance and exit zones due to a different heat conduction during the laser machining. Consequently, material removal rate, which is a productivity indicator, is calculated and a regressive model is proposed. Finally, due to the previous results, the investigation is focused on the problem related to the high production of spatter and an innovative nozzle is proposed to reduce the amount of spatter in the entrance zone of the holes.
In particular, the innovative aspect is the design and the application of a novel nozzle in laser microdrilling, which is able to reduce the deposition of melted material and spatter directly during the laser process, modifying the fluid-dynamic field. A suction effect, due to a back pressure generated during the laser microdrilling process, moves away the particles of the removed material, which is melted and vaporized by the laser beam. The performances of the proposed novel nozzle and the traditional nozzle, used to perform laser micromachining, are compared in terms of production of spatter and melted material.
It is demonstrated that the amount of spatter can be reduce by changing the gas flux during the laser process and suction effect can efficiently remove both drops of melted material and spatter around the machined holes, increasing the hole quality and without decreasing the high productivity of the pulsed fiber laser.
The proposed solution allows to stress the positive features of pulsed fiber lasers, in terms of high resolution and high productivity, and to solve the problem related to hole quality, in terms of spatter and melted material due to quite long pulse width, by means of the use of the proposed innovative nozzle.

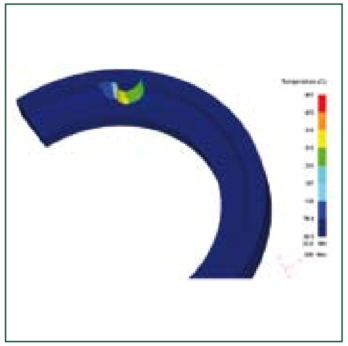
FINITE ELEMENT METHOD OF MILLING OPERATIONS

Gaetano Pittalà

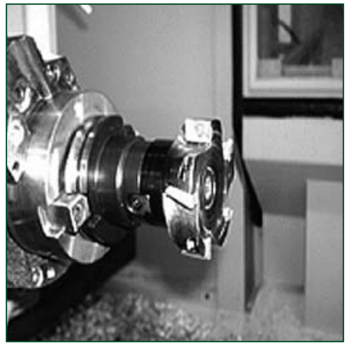
The aim of this work is the investigation of the finite element method of milling operations. Milling operations are very common in several industrial sectors, like aeronautic, aerospatial, medical, race, etc. The prediction of the performances of cutting process and the influence of the process parameters on the product quality is important for tool and process design. The Finite Element Method (FEM), applied to machining, is able to predict the cutting forces, stresses and temperatures of the process. These physical quantities are useful to design the cutting tool and determine the best cutting parameters.
The increasing productivity challenge together to the increasing cost pressures and changing environmental awareness has led manufacturing industry to give critical considerations to the strategy of machining and the use of conventional coolant in machining process. For materials difficult to cut, like nickel based alloys and titanium alloys, the adoption of High Speed Milling strategy is limited to the milling tool capability. It is crucial to know the mechanical and thermal load acting on the insert changing cutting parameters. The FEM method turns out to be suitable to know the milling tool condition, in term of stresses, temperatures and chip morphology.
The objective of this research is to provide a powerful analysis tool to design and optimize the cutting process. Milling operations have been considered and different materials have been used.
The idea is to be a support for high –value added machining operations, like hard to cutting materials and green cutting.
The general problem is referred to the prediction of the interaction between work piece and tool during machining.
This interaction is very complex, because several physical phenomena are concerned, from micro to macro scale. The workpiece and the tool are in contact due to the relative movement, at determined cutting speed, depth of cut, feed rate and cooling fluid.
During the operation the wear of insert causes a modification of its geometry, and then the interaction tool-workpiece changes.
In addition the chip removal and dynamic performances of the machine is linked each other.
The machine tool structure vibrates and then influences the cutting process and so on. In some circumstances the dynamic characteristics of the machine tool can be relevant and influences the chip removal. This produces big cutting force and then a high wear of the insert.
It is opinion of the author that the FEM tool can be suitable in the explanation of the lack of prediction of the theory of chatter, analyzing the process damping.
The simulation of milling operations should be a support to the milling tool design and useful to the optimization of cutting process.
From top management point of view the increasing productivity together with high quality level are the principal challenges.
Who makes milling tool bodies, inserts and coatings must put in the market new products with improved performances, in terms of long tool life and increased productivity, and able to cut "new" materials. This means a big experimental effort where several variables are concerned, with the consequence of large development time. The FEM tool can be useful for the analyst to design appropriately the cutting process and reduce the development time of new products.
Who is production responsible is interested to select the right cutting parameters with the aim to increase the productivity maintaining the same quality level or better. Another issue is to avoid defects during the machining. This is very important in the production of a single piece of an expensive material.



1. Single tooth milling tool



2. Milling simulation of titanium alloy, for cutting speed of 157 m/min, feedrate of 0.1 mm/tooth and depth of cut of 1mm



3. Multi tooth milling tool

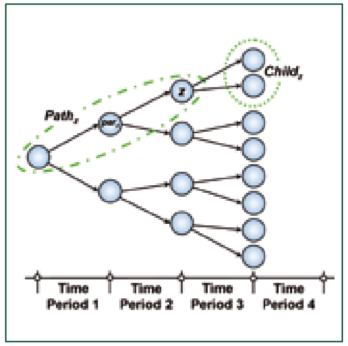
The FEM tool can be useful for the production analyst to design appropriately the cutting process, so to know the impact of cutting parameters.
Today the reduction of machining production pollution is an important issue for the actual society. Increasing cost pressures and changing environmental awareness has led manufacturing industry to give critical considerations to the use of conventional coolants and traditional cooling techniques in machining processes. This means new challenges to the modeling, in terms of capability of the method of analysis, and in terms of analysis of new machining configurations.
In this work the FEM simulation is carried out using explicit and implicit formulation. First milling tests using single tooth milling tool (Fig. 1) have been carried out. Two materials have been selected, continuous chip one and segmented chip the other one. Then the material law has been calibrated using two approaches, using the OXCUT software, developed at the ERC/NSM (Ohio State University), and the 2D FEM approach.
The calibration method was performed in collaboration with the lab. ERC/NCM in Ohio State University, that in the 1980 developed the finite element method applied to machining.
Sensitivity analyses about friction model and geometrical model have been performed.
The measured cutting forces are compared to finite element modeling.
The results show a good agreement between simulation and experimental results (Fig. 2).
Milling tests using multi tooth milling tool have been performed (Fig. 3). New inserts and chipped inserts were used. In this case 2D FEM simulation have executed, and the results show an acceptable agreement, also regard to chipped inserts.

MULTI-STAGE STOCHASTIC PROGRAMMING TO DESIGN FOCUSED FLEXIBILITY MANUFACTURING SYSTEMS

Walter Terkaj

Manufacturing Flexibility is seen as the main answer for surviving in markets characterized by frequent volume changes and evolutions of the technological requirements of products. However, the competitiveness of a firm can be strongly affected by capital intensive investments in system flexibility. Manufacturing Systems Design must provide effective solutions during all system lifecycle; therefore, systems should be endowed with a flexibility level tailored to the production problem. A System Design framework has been proposed starting from the technological analysis of the set of products that the manufacturing system will have to produce. Within the system design framework, the core activity consists of applying a design method to efficiently address the complexity of the problem that is enhanced by the uncertain environment and by the dynamics of the system lifecycle. Indeed, the design of evolving manufacturing systems requires a careful study of the production problem over the whole system life-cycle. The manufacturing systems can cope with the changes in the production problem by exploiting existing characteristics or by adopting system reconfigurations.
The addressed production problems are characterized by two main types of uncertainty: demand variability (external uncertainty) and machine failures (internal uncertainty). The uncertainty and the evolution of the production problems have been modeled by means of a scenario tree (Fig. 1). The scenario tree is composed of nodes representing the outcomes of a set of random variables defining the production problem characteristics. Each scenario node *z* is characterized by a unique parent node (par_z) and by a realization probability. Each level of the scenario tree represents a time period (e.g. six months, one year, etc.) and is associated with a time stage (st_z). Each node is associated with a path linking the root node with the node itself ($Path_z$). Each path from the root node to a leaf node in the last time period identifies a scenario. Finally, each node is associated with its set of child nodes ($Child_z$).

A manufacturing system design model based on Multi-stage Stochastic Programming has been developed, since this mathematical technique allows to cope with uncertainty. The system design solutions consist of a capacity plan with an initial system configuration and possible system reconfigurations. Problems formulated as Multi-stage Stochastic Programs present a relevant computational



1. Scenario tree representation

complexity as soon as the dimension of the scenario tree increases, both regarding the number of time stages and the number of scenario nodes. In literature there are two main approaches to solve this kind of problems: (1) the Deterministic Equivalent Problem (DEP), where the stochastic problem is formulated as monolithic model considering all the constraints related to the different scenarios; (2) decomposition algorithms exploiting the structure of the problem by solving independent subproblems. An algorithm based on Benders decomposition has been developed to efficiently address the problem of multi-stage stochastic capacity planning. The algorithm consists of two levels: at the first level the problem is decomposed according to the type of decisions to be taken in each scenario node (scenario node-wise decomposition), while at the second level the resulting subproblem is further decomposed according to time horizon (stage-wise decomposition). The performance of the decomposition algorithm has been tested over a set of test cases that are defined in Table 1. The test cases are characterized by the number of time stages (*S*), scenario nodes (*N*), binary variables (*BinVar*), continuous variables (*ConVar*) and constraints (*Cons*). The performance of the decomposition algorithm and the DEP formulation are compared in terms of solution time (*Sol*), upper bound (*UB*), lower bound (*LB*) and gap between the bounds (*Gap%*). A time limit of 1000 seconds has been imposed. The results clearly show that the decomposition algorithm outperforms the DEP formulation.

Even if the system design framework can be applied to any type of Advanced Manufacturing System (AMS), the development of the solution methodology was aimed at addressing the design of Flexible Manufacturing Systems (FMS) and in particular of Focused Flexibility Manufacturing Systems (FFMS). FFMS is an innovative manufacturing system architecture that rationalizes the system flexibility by finding out the best trade-off between productivity and flexibility. The required level of system flexibility impacts on the architecture of the system and the explicit design of flexibility often leads to hybrid systems, i.e. automated integrated systems in which parts can be processed by both general purpose and dedicated machines. This is a key issue of FFMSs and results from the matching of flexibility and productivity that characterize FMSs and Dedicated Manufacturing Systems (DMSs), respectively. Focusing the flexibility of a production system on the specific needs represents a particularly challenging problem because, even if the customization of system flexibility provides economical advantages by reducing the investment costs, tuning the flexibility on the production problem reduces also some of the safety margins that allow to decouple the various phases of manufacturing system design and to react to production changes and unforeseen events. The testing experiments carried out to test the profitability of FFMSs have shown that an FFMS can yield a relevant economic advantage at a system level if a machine tool builder succeeds in developing dedicated machines requiring a lower investment cost and/or better machining performance. The results of the experiments have shown also that the FFMS solutions are quite robust when facing production problems characterized by changes and variability of the aggregate demand. However, when there are relevant changes in the type of operations to be executed, the profitability of an FFMS solution can be strongly reduced, thus increasing the competitiveness of a traditional FMS. Therefore, during the initial phases of the system design it is necessary to analyze the present and potential future production problems in the most precise way. Moreover, the stochastic programming approach is required to solve the FFMS design problem because the system flexibility can be focused only after a careful evaluation of the possible evolutions of the production problem.

PROBLEM CHARACTERISTICS					DETERMINISTIC EQUIVALENT PROBLEM				DECOMPOSITION ALGORITHM			
S	N	BinVar	ConVar	Cons	Sol [s]	UB	LB	Gap%	Sol [s]	UB	LB	Gap%
2	6	2458	4536	9784	25.0	335.8	335.8	0.0	0.9	335.8	335.8	0.0
3	21	8531	15876	34189	1000	385.8	332.9	13.7	2.1	383.8	383.8	0.0
4	51	20691	38556	83000	1000	436.5	372.4	14.7	5.0	398.3	398.3	0.0
5	111	45146	83916	180672	1000	149149	387.8	99.7	14.8	407.0	407.0	0.0
6	231	94120	174636	379963	1000	264529	411.7	99.8	86.2	451.2	451.2	0.0

Table 1. Comparison between DEP formulation and Decomposition Algorithm solutions

OPTIMAL PRODUCTION SYSTEM RECONFIGURATION POLICIES TO REACT TO PRODUCT CHANGES

Maurizio Tomasella

In recent years, owing to the global competition, companies often have to be able to operate in a dynamic environment, where products need to be frequently modified or even replaced, and production volumes considerably change from one time period to another, following the market demand. Changes in process technologies and in government regulations should also be faced with an increasing frequency. In such an environment, it is critical for the enterprise to choose the manufacturing strategy that best allows to achieve sustainable and competitive production systems, which will be used to provide the market with the products it asks for.
The design phase of the production system will determine, together with the system management phase, the system performance over time. The manufacturer should pay a lot of attention, in particular, to the design phase, also considering that the life of production systems is generally much longer than the life of the products it has to produce. However, production systems are traditionally designed (configured) and modified (reconfigured) only on the basis of current information on the product and, eventually, of forecasts on expected future production volumes.
A critical point concerns the analysis and modelling of production requirements over time, needed as a prerequisite to define which different configuration solutions for the same production system are needed to satisfy these requirements, and which solutions appear to be the *optimal*.
In the present dynamic context, the evolution of the production system has to match closely with that of the products it manufactures. A change of products may force a change of the production system, thus also causing additional investments. Indeed, the technological product characteristics change, driven internally by the continuous improvement of the enterprise processes, and at the same time driven externally by the market. Thus, the production system may evolve because of the need to properly tune its configuration, in order to match with the product characteristics.
The basic idea behind this PhD research was that the production system can be easily and, even more important, profitably modified to react to one ore more product changes only if the whole evolution of products is considered when the reconfiguration decision is made.
In order to accommodate these changes, originated for instance by a modification of one of the product features, or by the change of the product material, or again by the introduction of a new product variant, or by the structural increase of production volumes, etc., new functions must be added to the manufacturing system (e.g. an additional spindle unit, or a new station) and/or existing functions must be adapted (e.g. the stroke of a motion axis, or the capacities of existing buffers).
In general, for each kind of change in the production requirements, a different type of reconfiguration is needed. The common denominator for all of these changes, is that for each system reconfiguration occurring during the lifetime of a system, a so-called *ramp-up* period takes place, which is the transition period it takes a manufacturing process/system to reach full-scale production at targeted levels of cost and quality. Shortening these periods is one of the main problems concerning the reconfiguration of manufacturing systems.
In the above described context, models supporting the reconfiguration of production systems should be characterized by an integrated view of product and production system evolutions. This PhD Thesis proposes decision support models based on this integrated view.

A first main result described in the thesis concerns the formalization of the design decision problem, and in particular the formalization of the integrated evolution of the production system and the production technological and demand requirements. This is achieved by couching the problem in the framework of Staochstic Optimal Control.
A second main outcome concerns the development of analytical models, in particular of an optimal policy (rule), to support the system designer in the optimal initial configuration of the production system, and in the optimal successive reconfiguration of the same, based on the known and forecast evolution of these production requirements.
This second achievement was obtained by using Dynamic Programming.
The provided analytical models and optimal policy have been tested on a number of cases, and have been used to derive insights regarding the behaviour of these policies in different settings of reconfiguration costs.
In particular, the reconfiguration of high power fiber laser sources, a technology introduced in the last decade in the manufacturing sector, mainly for welding and cutting applications, was investigated.
This application is particularly interesting because of the features of fiber laser sources, whose total installed power is given by the sum of the power of a number of modules. This modularity characteristic makes them possible, in principle, to be reconfigured over time, i.e. to have their total power modified from period to period, depending on the user needs and, ultimately, on the evolution of the technological specifications of the products the laser system (to which the fiber laser source belongs) has to produce. Clearly, the modification of the total power of the laser source results in a modification of the number of modules being installed from time to time. Currently, no decision support method aids the source end user to define its own needs in terms of installed power over time, based on the evolution of its production requirements; this basically results in the initial purchase, by the end user, of a number of modules providing an overall total power which largely exceeds what he will need in the future. The optimal policy presented in this thesis fills in this gap.
All this is developed, in the context of the thesis, with reference to the end user of the laser source. However, some discussion is provided concerning the problem of the source manufacturer. The problem is that, currently, the prices of modules are so high that, even if the end user would know and use the optimal policy in making its design decision, the answer will generally be that it is optimal to install an initial oversized power, and then not to change anymore the number of modules; this is all only because of these prices. In order to enhance the business related to sales of laser modules, the laser manufacturer is interested in knowing the minimum price for the modules beyond which the purchase of new modules by the end user starts to be convenient.
This will enable the end user to initially purchase only the power he strictly needs (or just a little bit more), and then to eventually add new modules in the future, if it is needed. Moreover, the easy modification of the number of modules facilitates the circulation of these modules, and in turn enables the investigation of potential new business schemes such as the rental of modules, with possibly new kinds of contracts and maybe services the manufacturer can deploy to the end user.
Another application is the one obtained by modifying the general analytical method to the reconfiguration of just the system overall capacity, intended as the number of pieces produced in a given time window, was also developed, as a new way of planning system capacity over time. This quantitatively takes into account, in the decision process, the weight of the ramp-up phenomenon.
Finally, the analysis of the optimal reconfiguration policy proposed in the work led to an interpretation of the analytical elements of this policy as a measure of the degree of reconfigurability of a production system, i.e. of how much the system is likely to be reconfigured, in response to some given modification of production requirements.