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Application of process parameters in planning and technological documentation: CNC machine tools and CMMs programming perspective

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Abstract

This article focuses on the role and application of process parameters in technological process planning (TPP) and technological documentation (TD). The challenges and complexity involved in computer numerical control (CNC) machine tools and coordinate measuring machines (CMMs) programming have been taken into consideration with reference to the TD. The article presents the use of different programming platforms and implementation of them in technological process planning. The subtractive manufacturing and related measurements that are required during the TPP and TD phase have been taken into consideration. The findings and suggestions enable planners to incorporate the existing programming platforms and tools in the TPP and TD.

Keywords: planning; CAPP; manufacturing process

1. Introduction

Manufacturing engineering faces the new challenges regarding preparation of technological processes, among others, the need of using statistical methods [1], rapid development of internet technologies [2,3] or advanced measuring techniques [4]. These challenges are the result of new developments in the construction of CNC machine tools and coordinate measuring machines (CMMs). Software or cutting tools developments are also crucial in the case of existing need of the process plans improvements. This section presents the main stages of process planning, the structure of contemporary process plans and discusses the need of new developments.

1.1. Introduction to process planning

Technological process planning (TPP) plays an important role in subtractive manufacturing processes. The majority of TPP tasks take place before the implementation phase [5]. However, a process plan may be changed during the implementation. The TPP usually involves a combination of several challenging phases (see Fig. 1). Currently, a significant number of software have been used in order to increase the effectiveness of the TPP [6]. Although there are computer aided process planning (CAPP) tools available on the market (e.g. ADEM [7]) and the new e-CAPP [2] tools, the cloud-

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based tools [3] or the feature-based process planning approaches [8], to date, most of manufacturing companies use hybrid (i.e. a blend of software and conventional approaches) methods of process planning. Software is used for the choice of tools and process parameters (e.g. Tool Guide from Sandvik [9], ITA from Iscar [10]), and also necessary calculations of tool paths (e.g. Catia from Dassault Systèmes [11] or NX from Siemens [12]). Conventional approaches require the use of experience and knowledge of a process planner and know-how of a company. Important information about the condition of machine tools, skills of operators, results of previously completed processes are taken into account during the phase of conventional process planning. Conventional process planning also means, in this case, that a process is created without the significant computer assistance. The main structure of technological process (see Fig. 2) is usually divided into technological operations which are the main components of process [13,14]. Each operation requires the use of individual workstations which can be defined as the separate machine tools or automatized cells.

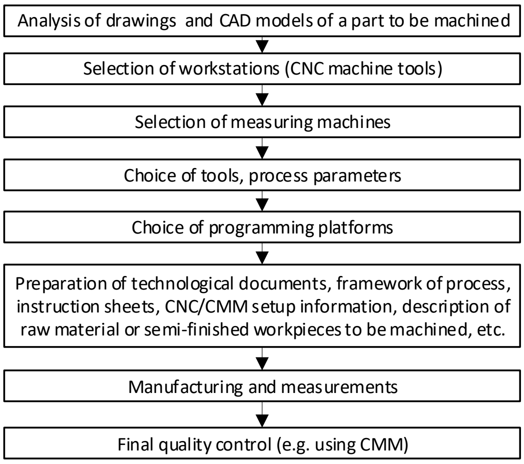

Fig. 1. The stages of TPP including manufacturing and measurements

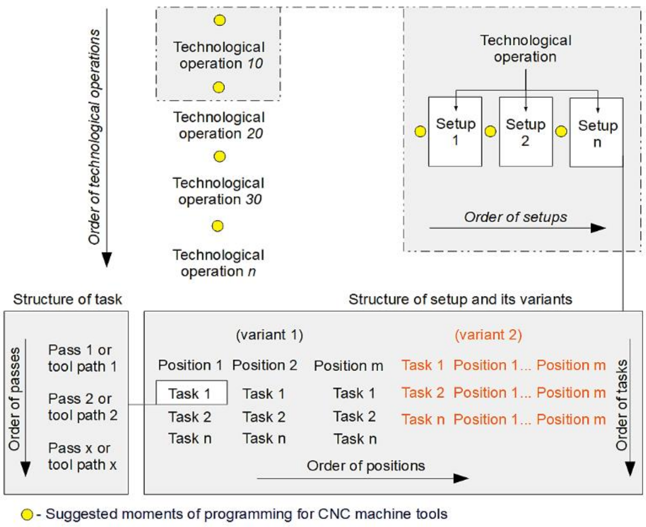

Fig. 2. The structure of technological process including programming tasks

Each technological operation is frequently divided into setups (called also as subjobs [15]). Setup consists of positions or machining tasks. Based on the authors' experience, depending on the complexity of machining, the machining task can play, in reference to position, the subordinate or the overriding role. For instance, in the case of drilling of several holes, located on the perimeter of a shaft, on the 4-axis milling machine tool with a rotary table (A - axis), the position plays subordinate role because there are several positions within one complex task. The machining tasks consist of passes or individual tool paths in which the allowance is removed from the workpiece. There are also presented in Fig. 2 the moments in which CNC programming takes place. Programming may be carried out before the realization of the first technological operation while technological documentation is prepared. In this case, all technological operations can be programmed using different programming platforms or selected operations can be programmed by using the same platform. The next possibility concerns programming before realization of each operation after completing the previous one. This is beneficial, among others, if the results of machining in previous operation are considered for the preparation of the following one. In the case of conversational programming it is a typical procedure because usually programming process is realized directly at a machine tool by an operator. If the number of manufactured parts is small, programming of CNC machine tool may be also carried out between each setup or even each task.

1.2. The need of new developments

There is the great need for wider discussions on process planning (see Fig. 3). Manufacturers operate in the digital era in which many tasks are performed by the use of computers.

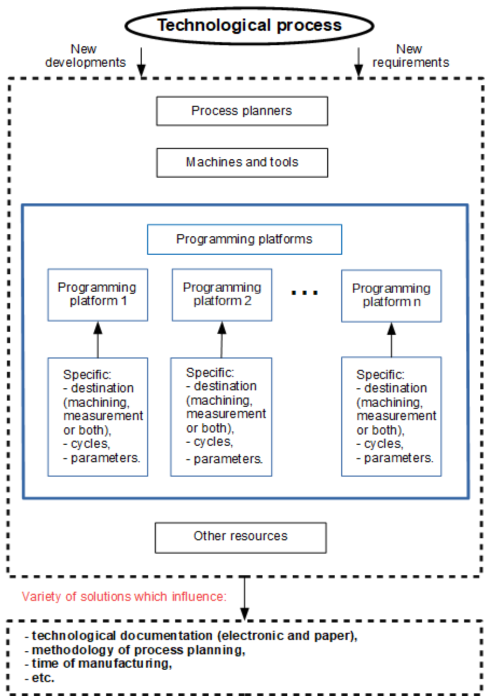

Fig. 3. Clarification of the necessary research

New trends and solutions often lead to the need of change of procedures, which have been used so far. This is visible in the case of process planning. Developing the templates (documentation of technological processes) requires the consideration of structure of various programming platforms which often differ, and also manufacturing processes, which are developed intensively. This study is, hence, the preliminary overview of existing solutions and challenges and an attempt to find the new approaches which can improve the use of programming platforms and process parameters – both in measurements and subtractive manufacturing.

2. Issues of CMMs programming

Coordinate measurements are usually performed for the quality control. They can be performed using coordinate measuring machines (CMMs) or directly on machine tools. Measurements performed on CNC machine tools are called “on machine measurements” (OMM). Coordinate measurements of products are conducted mainly at the end of a production process but they can be also performed after selected phases of process (refer with Fig. 2 and Fig 4). The such measuring systems may be equipped with contact and non-contact measuring probes [4,16]. The information concerning the parameters of coordinate measurements should be included in the technological documentation of a product.

A measurement program may be prepared using both on-line and off-line modes (see Fig. 4). The example of software which enables programming of coordinate measurements with the use of two mentioned modes is Calypso software produced by the Carl Zeiss company. The Calypso software enables conducting simulations of coordinate measurements including e.g. styluses of measuring probes, measuring probes, a rotary table and coordinate measuring machines which are planned to be used during real coordinate measurements. Having the possibility of performing simulations, an operator of a CMM can check the occurrence of collisions between styluses of a measuring probe and a measured workpiece. In the case of measurements conducted in a production environment, off-line programming of measuring probes mounted in spindles of CNC machine tools is also possible.

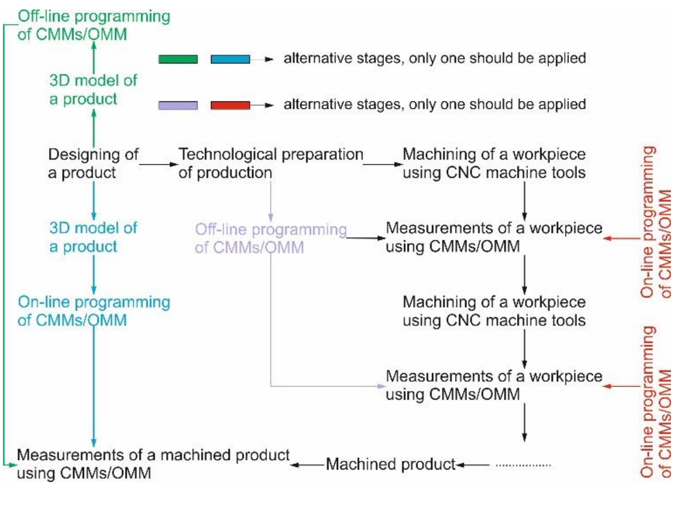

Fig. 4. The stages at which coordinate measurements are possible

The Productivity+ software produced by the Renishaw company is dedicated for off-line programming in a production environment. Using that software a user has the possibility of optimizing a program created for measurements.

3. Programming platforms for CNC machine tools

Programming platforms are the unique software-based solutions which enable to develop CNC programs using the specific programming method/approach. Most of the CNC controllers enable to run programs formulated as the set of blocks of data describing the tool paths and technological parameters. These programs are usually created by programmers using three known approaches - direct programming, conversational programming and CAM software. Direct programming concerns developing of code, based on the manuals from producers of controllers. Conversational programming is based on the graphical interfaces which allow to build the technological operation with an efficient and easy way (usually by operators who are not experienced programmers) by using dialog windows describing programmed geometry of a part. CAM software is used frequently in order to prepare machining sequence using PC software and generate a program by specified postprocessor. There are different types of controllers for which exist very specific functions (e.g. miscellaneous M-codes and preparatory G-codes). Therefore, direct programming should be analysed separately for each controller although there are many similarities. For instance, the standard cycles (e.g. plane milling cycle, drilling cycle, taping cycle) may be programmed differently depending on the format of block and parameters. Moreover, among conversational programming and CAM programming platforms there are also differences which force programmers and process planners to define some parameters (e.g. strategies’ types) individually for used platform taking into account their limitations. Table 1 is an example of differences and presents exemplary parameters and strategies of rectangular pocket milling in different programming platforms. Other differences can be presented based on the analysis of other standard cycles implemented in CNC controllers. In the case of examples presented in Table 1 standard cycles used in direct programming (e.g. Pronum CNC controller) have much less parameters than similar algorithms which are used in CAM programs. In the case of conversational programming there are some similarities to windows of CAM programs but CAMs offer more flexible choice of ready-to-use machining strategies and technological parameters, and also postprocessing. The names of parameters also differs although it concerns similar machining tasks.

The above described differences cause some problems of developing of unified technological documentation. The templates which are usually used in process planning should include the gaps for definition of parameters present in various platforms. There is a challenge to create, in the technological documentation, the gaps which enable to define the most important parameters and take into account all options in existing programming platforms. The choice of different programming platforms for the aim of one technological process, which consists of many technological operations, may lead to the need of exploring the use of these platforms by process planners.

Table 1. Exemplary parameters and strategies of rectangular pocket milling in different platforms on the basis of [17] and sources in Acknowledgments

Haas conversational programming	Tool definition (e.g. center drill, end mill) and technological parameters: rotational speed (*n*) , feed (v_f)
	Geometry definition: depth of pocket, starting position in X axis, starting position in Y axis, axial depth of cut, width of a pocket, length of a pocket, rapid plane definition: R-value defining the plane of rapid moves
	Machining strategy: only one available for selected tools
Sinumerik conversational programming	Type of input: simple, complete
	Tool definition (tool type, D-number) and technological parameters: feed rate (v_f), cutting speed (v_c) or rotational speed (*n*), radial depth of cut (a_e), axial depth of cut (a_p),
	Geometry definition: reference point, starting point (in three axes), width of pocket, length of pocket, corner rounding, rotation of pocket, allowance in XY plane, allowance in Z plane,
	Machining strategy: type of insertion (vertical, helical, ramp cutting), type of machining (chamfer, wall, complete, re-machining)
Pronum direct programming	Tool definition (cutter, D-number) and technological parameters: feed rate in XY plane (v_{fxy}), feed rate in Z axis (v_{fz}), rotational speed (*n*), axial depth of cut (a_p),
	Geometry definition: reference plane, plane defining the depth of pocket, allowance for finishing, length of pocket, width of pocket, centre of pocket in X axis, centre of pocket in Y axis, corner rounding, rotation of pocket
	Machining strategy: only one is available
CATIA CAM programming (various parameters can be selected in defined Catia software windows)	Tool definition (tool type) and exemplary technological parameters: feedrate (v_f) parameters (e.g. feedrate of approach, retract, machining), parameters of feedrate reduction in corners, radial (a_e) and axial (a_p) depth of cut parameters, parameters of finishing, parameters of HSM machining, spindle speed (*n*), possibility of automatic computation from tooling feeds and speeds
	Geometry definition: choice of geometry from a CAD model, definition of chuck for a collision checking
	Machining strategy: e.g. inward spiral morphing, outward spiral morphing, concentric, offset on part Zig-Zag, offset on part One -Way, back and forth, inward helical, outward helical
NX CAM programming (various parameters can be selected in defined NX software windows)	Tool definition (tool type) and exemplary technological parameters: feedrate (v_f) parameters (e.g. feedrate of approach, retract, machining), radial (a_e) and axial (a_p) depth of cut parameters, parameters of finishing, algorithm of HSM machining, spindle speed, possibility of automatic computation from tooling feeds and speeds
	Geometry definition: choice of geometry from a CAD model, definition of chuck for a collision checking
	Machining strategy: e.g. Zig, Zig, Zig-Zag, Trochoidal, etc.

To avoid these problems enterprises may purchase CNC machine tools with the same CNC controllers and they can also use the only one programming platform. It enables to teach employees the proper use of selected platform, so they are not forced to explore different solutions and the necessary training is usually cheaper. Unfortunately, this approach may cause, in some cases, that a company loose other valuable solutions by excessive concentration on the implementation of the only one platform. Therefore, this problem can be solved by choosing the programming platform which is intensively developed by its producer (e.g. software which is updated every year or more often), avoiding the standardization of documentation (e.g. applying internet-based, flexible templates, which are susceptible to editing, and creating the departments/positions in the organizational structure of company in order to update existing templates.

4. The choice of significant process parameters and strategies for the aims of CNC machine tools and CMMs programming

Technological documentation should consist of efficient set of data which enables CNC programmers and operators to perform machining tasks correctly. There are important groups of parameters (input data) which differ for various processes (see Table 2). In the case of cutting and grinding there are parameters regarding feed rates, cutting speeds and these which concern the removed allowance. Additional parameters should also be considered if the machining process concerns the tool. It exists for grinding wheels which are shaped in conditioning processes. Electro discharge machining requires the definition of electrical parameters and feed rates. Laser machining requires to set laser output parameters, which substitute the parameters of a main drive in cutting and grinding, and feed rates of laser head in machining zone. In the case of hybrid machining processes, additional parameters regarding the special devices necessary for the realization of hybrid process have to be included in the technological documentation. For instance, in ultrasonic assisted processes, the parameters of ultrasonic generator are programmed. Laser assisted machining, similarly to conventional laser machining, requires the use of laser output parameters.

All numerically controlled machine tools enable to use various toolpath strategies. The strategy may be defined as the shape of the tool path and is selected by a process planner in order to formulate NC-codes for the efficient course of process. Numerical control allows to apply different, often complex, strategies. The strategies are chosen based on the tool type, allowance, hardness, part geometry, method of clamping, etc.

Abovementioned Table 2 presents, hence, examples of the most important technological parameters for selected subtractive machining processes. They should be considered in the process plans when templates are filled out. Moreover, in the templates regarding the specific technological operation, attention of process planner should also be paid on the method of setup of a workpiece on CNC machine tool used for the planned technological operation. The proper presentation of the method of setup requires a drawing/or CAD models (prepared in assembly modules) which contains the fixture, workpiece, used coordinate system and other elements important for operator of the specific machine tool.

The specific parameters are also used in the case of measurements performed both on CNC machine tools and on coordinate measuring machines. Table 3 presents important parameters of measurement performed on CNC machine tools and coordinate measuring machines. In the case of CNC machine tools, there are different types of measuring probes (contact and non-contact ones). They enable to measure workpieces and tools based on parametric programs (macros). Nowadays measurements on machine tools may be performed also between separate machining tasks. The requirements of measurements force process planners to define specific parameters of measurements in the TD.

Table 2. Examples of technological parameters of selected processes which should be considered in the process plan

Process name	Examples of necessary parameters
Cutting processes *(e.g. turning, milling, drilling)* ***Exemplary machine tool:*** *DMC 635 V from DMG*	**- tool characteristics** (e.g. geometry, material) **- parameters of a cutting layer** (e.g. axial depth of cut (a_p), radial depth of cut (a_e)), **- a velocity of cutting** (v_c) and **- selected parameters of feedrate** (e.g. f_t or f_n) **- machining strategy** (e.g. shape of tool path)
Grinding (e.g. grinding of flat surfaces) ***Exemplary machine tool:*** *FS 640 C CNC from Geibel & Hotz*	**- tool characteristics** (e.g. geometry, material) **- parameters of a cutting layer** (e.g. axial depth of cut (a_p), radial depth of cut (a_e)), **- a velocity of cutting** (v_c) and **- selected parameters of feedrate** (e.g. f_n) **- selected parameters of conditioning of grinding wheel (**e.g. depth of dressing (a_{ed}), federate of dressing (f_d)) **- machining strategy** (e.g. shape of tool path)
WEDM *(e.g. wire EDM)* ***Exemplary machine tool:*** FA10S from Mitsubishi	**- type of wire** **- electrical parameters** (e.g. voltage (u) , current (I), time of impulse (t_i)) **- geometrical parameters and machining strategy** (e.g. diameter of wire (d_w), shape of tool path) **- other parameters** (e.g. wire tension (t_w), velocity of wire (v_w), feedrate of wire (f_w), etc.)
Laser machining ***Exemplary machine tool:*** *Lasertec 20 linear from Sauer*	**- laser output parameters** (e.g. pulse frequency (p_f)) **- a feedrate** (f_t) **- machining strategy** (e.g. shape of toolpath)
Hybrid processes *(e.g. ultrasonic assisted grinding)* ***Exemplary machine tool:*** *Ultrasonic 20 linear from Sauer*	**- tool characteristics** (e.g. geometry, material) **- parameters of a cutting layer** (e.g. axial depth of cut (a_p), radial depth of cut (a_e)), **- a velocity of cutting** (v_c) and **- parameters of feedrate** (e.g. f_t) **- parameters of additional equipment of a hybrid machine tool, for example process parameters of ultrasonic generator** (e.g. f_{US}) **- machining strategy** (e.g. shape of toolpath)

These parameters, similarly to machining, may be defined differently depending on the type of measuring device and used programming platform. In the case of using measuring probes working in the single probing mode number and a distribution of measured points on measured surfaces may be used as an example. In the case of scanning probes parameters may include a distribution of scanning lines on surfaces of investigated products and an applied scanning velocity. Parameters which are defined for coordinate measuring machines concern the definition of measurement plan based on CAD models of parts. Technological documentation which includes the mentioned groups of parameters should be editable. The elimination of paper versions of documents is still a big challenge, even in developed companies. Technological documents, e.g. these which are available in the internet cloud could solve some problems if the structure of cloud is readable for users. Table 3 includes only examples of parameters dedicated for coordinate measurements performed using CMMs and CNC machine tools equipped with measuring probes. In the case of using other measurement systems, it may be necessary to apply different parameters, than those presented in Table 3, during planning a technological process.

Table 3. Examples of parameters for CNC machine tools and CMMs

Type of measurement	Examples of necessary parameters
	CNC machine tools
Measurements of workpieces with the use of measuring probes	probe configuration (e.g. diameter of a ruby ball) scanning speed for scanning probes (v_s) number of measurement points (n_p) distribution of measurements points (d_{mp}) parameters of feedrate (v_f) parameters of workpiece geometry (e.g. dimensions of pocket)
Measurements of tools with the use of measuring contact probes and laser probes	probe configuration (e.g. calibration parameters) parameters of feedrate (v_f) parameters of tool geometry (e.g. type of a tool)
	CMMs
Measurements of workpieces with the use of CMM	probe configuration (e.g. stylus type, length, etc.) scanning speed (v_s) number measurement points (n_p) distribution of measurement points (d_{mp}) time of masking of measurement points (t_{mp}) length the travel distance (l_{td}) methods of probe radius correction (e.g. based on Bézier curves, based on linear interpolation) type of scanning path (e.g. circular interpolation) type of associated element (e.g. Gauss) parameters of filtration process outliers elimination alignment strategy (e.g. strategy RPS 3-2-1)

5. Possible new approaches

Abovementioned examples reveal that variety of solutions available for process planners nowadays may cause the difficulties in developing the standard procedures and standard templates. Therefore, it is necessary to carry out following suggestions in the future (i.e. in relation to the use of different programming platforms for CNC and CMMs):

- developing the ISO standards of internet-based templates.
- developing the flexible (editable), user-friendly templates.

- developing internal standards (i.e. performance standards) in manufacturing firms, which point the required parameters for each measurement or machining operation.
- creating the digital library (see Fig. 5) where the exemplary processes could be added and discussed among process planners in order to improve existing processes and to develop new ideas.
- increasing the collaboration between universities in order to work out the appropriate procedures.

The digital library of process plans could lead to the rise of some new ISO standards adequate for changing technologies of XXI century on the basis of the best solutions in the area of TPP. Universities could use the developed solutions for the teaching of process planning basics (also in e-learning). In this context, the industrial organizations could have the opportunity to present or share the new solutions with academia.

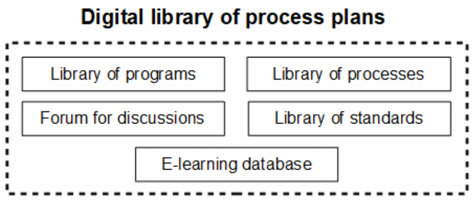

Fig. 5. The simplified structure of digital library of process plans

6. Conclusion

TPP is one of the most important activity for enhancing performance of manufacturing operations. The article presents the complexity involved in TPP and the potential use of different programming platforms, which require the use of specific parameters of machining and measurement that are need to compatible for use in different platforms. In addition, it presented a detailed discussion about application of parameters in TD and TPP phases in relation to manufacturing processes.

The appropriate choice of programming platforms may lead to the increase of effectiveness in manufacturing. If the high-quality documentation is prepared, the renewal of manufacturing of the same part should be cheaper and faster. The process of creation of correct and transparent process plans is strongly related to existing programming platforms, machine tools and coordinate measuring machines. For instance, it is necessary to have a precise set of parameters, strategies, fixtures, etc. in TD. The possible solution of creating the unified documentation accurate for different programming platforms shall be achieved by the use of internet-based and editable templates with the possibility of adding diagrams, pictures and movies. Furthermore, existing computer-aided process planning platforms should also meet the requirements of different programming platforms, challenges of contemporary production (e.g. Industry 4.0 concept [18], design of experiments [1]), networking, etc. Moreover, the standardization enables to solve the problems involved in programming platforms; however, it can also prevent the positive effect of new developments. Therefore, future research shall be carried out to investigate possibility for developing new standards focusing on the existing proven best practices. In this context, the investigation of the possibility for integration of the newest technologies (e.g. additive manufacturing techniques) related factors is also crucial.

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Table 1 is partially prepared on the basis of the authors' analysis of controllers' interfaces and software available in laboratory: Haas controller (www.haascnc.com), Sinumerik controller (www.siemens.com), NX CAM (www.siemens.com), Catia (www.3ds.com). Table 2 and Table 3 are prepared on the basis of author's experience.

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