PRELIMINARY DESIGN OF 3-AXIS MACHINE TOOLS: SYNTHESIS, ANALYSIS AND OPTIMISATION

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ABSTRACT: This paper presents an overview of a computer-aided design system for the preliminary design of 3-axis metal cutting machine tools. The design system consists of integrated software tools for the synthesis, analysis and optimisation of the preliminary structural configurations (layouts) and the preliminary geometry of 3-axis machine tools. During the synthesis the layout variants and their parametric CAD models are automatically assembled. Several analysis tools were developed for the evaluation of the synthesised variants: the validity, the feasibility, the volume, the interference, the static and the dynamic analyses. A search for optimal preliminary geometry and optimal layout can also be carried out.

KEYWORDS: machine tool design, preliminary design, configuration design, layout design, CAD/CAE

1. INTRODUCTION

Today, there are many novel design methodologies, CAD tools, artificial intelligence methods and advanced information technology tools – such as high-speed computers, large memory and storage capacities, distributed computing – available that may support the systematic machine design and enable the synthesis and evaluation of thousands of design alternatives within a reasonable time. The integrated use of these tools and technologies could open new possibilities in the design of machine tools, especially in the early phases of the design process where the major decisions underpin all subsequent decisions.

Several design methods and tools can be found in the literature on the conceptual design of machine tools – some examples are [1], [2], or [3]. These systems are either not appropriate for the systematic exploration of numerous design variants or lack the evaluation and optimisation of the explored variants.

This paper presents an integrated computer-aided design system that supports the synthesis, analysis, and optimisation of the preliminary design of 3-axis machine tool structures. This design system is able to synthesise numerous design variants, analyse and evaluate these variants and perform optimisations. The paper focuses on the methods used for the exploration and exploitation of design variants: the description and synthesis methods and the qualitative analysis.

The first prototype of the design system was developed by Lipóth [4]. The second prototype was carried out by Németh [5]. During an international project, an industrial software version of the design system was developed where this system formed a module of a complex mechatronic design system [6].

2. THE DESIGN PROCESS

Figure 1 shows an overview of the design process that can be carried out within the design system. Using some layout parameters and layout constraints, one or a group of machine tools can be prescribed. The *layout parameters* describe certain requirements for the global structural configuration of 3-axis machine tools. The *layout constraints* are qualitative limitations for the resulting machine tool structures. During the *configuration* the parametric geometric models of the machines are synthesised from a parametric component library. After configuration, the machines can be evaluated with the help of the *analy-*

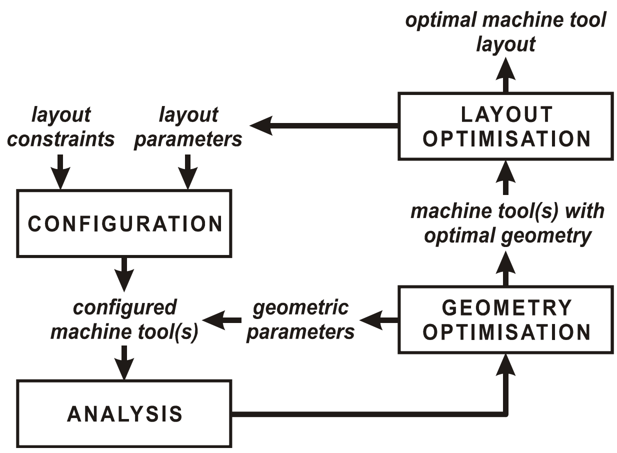

Figure 1. Overview of the design process

sis tools. Using the results of the analysis tools, objective functions can be formulated for the *optimisation of the geometry* of the synthesised machine structures. Here, the optimal values of the selected geometric parameters can be searched for. A higher-level optimisation – the *layout optimisation* – can also be performed. This is a search for optimal machine tool layouts where the machine tools having optimal geometry (after the geometry optimisation) are compared.

3. DESCRIPTION OF MACHINE TOOLS

The design system was developed for the design of the basic structural layout with preliminary geometry of *metal cutting milling-machine-like machine tools that have 3 linear axes*. The main function of such machine tools is to rotate the cutting tool and provide relative motion between the tool and the workpiece in order to perform the cutting operations. This section presents the *15 layout parameters* that were defined to describe the preliminary structural layout of machine tools.

3.1 Fixed Member and Vertical Guideway

The basic layout of a 3-axis machine tool structure consists of an open serial chain of four members, namely the headstock (HST) that holds the spindle (that rotates the tool), the member next to the headstock (NT_HST), the member next to the table (NT_TBL), and the table (TBL) that holds the workpiece to be machined. The member at one end of the chain is the HST, and the one at the other end is the TBL. One of the four members is fixed to the ground. For example, Figure 2 shows a machine where the NT_HST is the fixed member; or at machines *c)* and *f)* in Figure 3 the TBL is fixed. *There is a layout parameter to describe the place of the fixed member.*

The four members are connected by three linear guideways. The headstock guideway (HST_GW) connects the HST and the NT_HST; the middle guideway (MID_GW) connects the NT_HST and the NT_TBL; and the table guideway (TBL_GW) connects the TBL and the NT_TBL. The three drive directions of the linear guideways are perpendicular to each other and one of them is vertical. *There is a layout parameter that describes the place of the vertical guideway.*

3.2 Solid or Box-In-Box Headstock-Chain

The four members of a machine tool can be divided into two member-chains: the *headstock-chain* that contains the members from the fixed member to the headstock, and the *table-chain* that contains the members from the fixed member to the table. The design system is able to configure the machine tools in a manner that the layout of the headstock-chains can be either solid or box-in-box and the layout of the table-chains can be solid only. For example, the machine presented in Figure 2 is a 'full' solid-type machine because both the headstock-chain and the table-chain have solid layout. A solid layout has solid components and their construction is such that other components cannot move 'inside' them. Figure 3 *f)* shows a machine tool of a 'full' box-in-box layout because the machine has a fixed table (i.e. there is no table-chain) and the headstock-chain is of box-in-box type. The structural components of a box-in-box chain have typically frame-like shapes so that other components can move inside the frames. Machines *g)*, *h)* and *i)* in Figure 3 have mixed box-in-box and solid layout – i.e. the headstock-chains are of box-in-box type and the table-chains are of solid type. *There is a layout parameter that describes whether the headstock guideway is solid or box-in-box.*

3.3 Orientation of Spindle and Table

The spindle direction of any machine tool can be parallel with the drive direction of one of the three guideways. The spindle direction means the rotary axis of the spindle (see Figure 2). Similarly, the normal of the table plane – or shortly the table normal – of any machine tool can be parallel with the drive direction of one of the guideways. The table plane is a surface where the workpiece is clamped to. *There are two layout parameters to describe the direction of the spindle direction and the table normal, respectively.*

3.4 Description of the Guideways

Each linear guideway is constructed from *a long part and a short part* and these two parts are assembled to the adjacent members. Either the short part can move on its long counterpart or the long part can move on its short counterpart. In the design system the

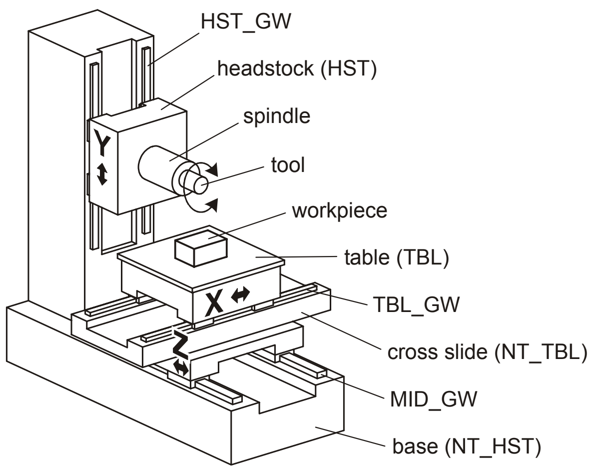

Figure 2. 3-axis milling machine (solid type)

frequently used guideway concept is applied where the long part is constructed from two rails, and the short part is constructed from four carriages. In Figure 2 all guideways have the construction where the short parts move on the long parts. Machines *i)* and *j)* in Figure 3 are such that the motions at the headstock guideways are realised in a way that the long parts move on the short parts.

The solid or the box-in-box type of the headstock-chain (see Section 3.2), in fact, is determined by the construction of the guideways – i.e. by the connection of the members. For instance, machine *g)* in Figure 3 has a solid table guideway, a box-in-box headstock guideway and a box-in-box middle guideway. Therefore, we distinguish solid and box-in-box guideways.

3.4.1 Solid Guideways

Each solid guideway has a specific direction which is a vector that orients the guideway. This vector is the normal vector of the guideway plane. The normal of a solid guideway can be parallel with one of the drive directions of the other two guideways. For example, in Figure 2 the normal of the table guideway is parallel with the drive direction of the headstock guideway. *There are three layout parameters to describe the orientation of the three solid guideways, and three layout parameters to describe the short-long relations of the solid guideways.*

3.4.2 Box-In-Box Guideways

A box-in-box guideway can be either ‘through’ or ‘none-through’, and either ‘coplanar’ or ‘opposed’: Figure 4 shows the four combinations. A box-in-box

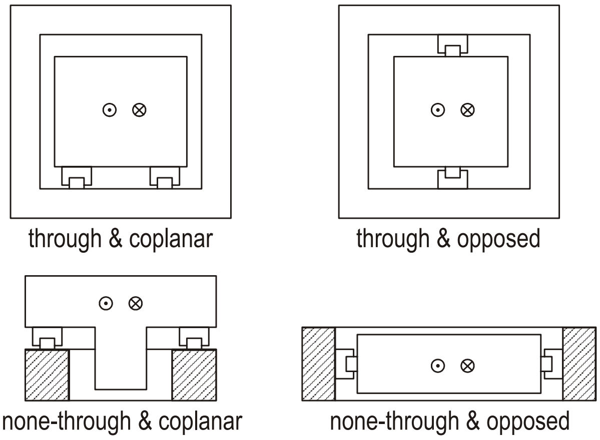

Figure 4. Types of box-in-box guideways

guideway is *through*, if the moving component moves through the stationary frame-like component inside its opening. For example, in Figure 3 the headstock guideways of machines *f)*, *g)* and *i)* are through box-in-box guideways. A box-in-box guideway is *none-through*, if the moving component does not move through the opening of the stationary frame but moves parallel with the front-face of the frame. For example, in Figure 3 *f)* the middle guideway and the table guideway are none-through box-in-box guideways. Both the through and the none-through box-in-box guideways can be either coplanar or opposed. A box-in-box guideway is *coplanar*, if the rails (as well as the carriages) are placed on the same surface or plane. A box-in-box guideway is *opposed*, if the rails (as well as the carriages) are placed on opposed surfaces or planes. For instance, machines *g)* and *h)* in Figure 3 have coplanar headstock guideways and opposed

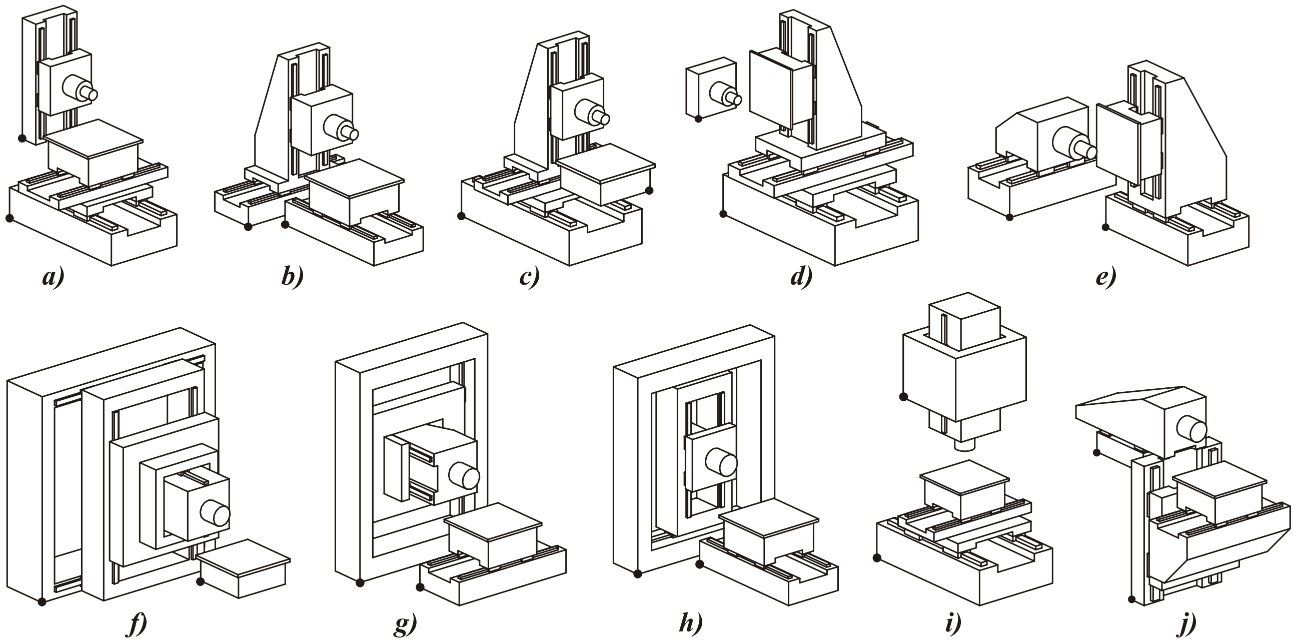

Figure 3. Various 3-axis machine tool layouts

middle guideways. *There are four layout parameters to describe the box-in-box guideways.*

4. SYNTHESIS

By assigning values to the layout parameters one or a group of machine tool layouts can be prescribed. Then the design system configures and assembles the parametric geometric models from parametric structural components in a manner that each geometric model is assembled from five components because the fixed member is composed of two components. The two components of the fixed members are indicated by dots in Figure 3.

4.1 The Components

In the component library of the design system there are more than 80 components that have parametric shapes and dimensions. The components are classified into a hierarchy where the six major component classes are the following:

- *'Fixed Headstock'*: if the fixed member is the headstock, then one of the two components of the fixed member is realised from a component of this class [e.g. see machine *d)* in Figure 3].
- *'Moving Headstock'*: if the fixed member is not the headstock, then the headstock member is a moving member and is realised from a component of this class. For example, except machine *d)* in Figure 3 each machine has a moving headstock component.
- *'Fixed Table'*: if the fixed member is the table, then one of the two components of the fixed member is realised from a component of this class [e.g. see machines *c)* or *f)* in Figure 3].
- *'Moving Table'*: if the fixed member is not the table, then the table member is a moving member and is realised from a component of this class. For instance, except machines *c)* and *f)* in Figure 3 each machine has a moving table component.
- *'Cross Slide'*: if the members NT_HST or NT_TBL are not fixed then such members are realised from the components of this class. A cross slide component has two perpendicular guideways. For example, a cross slide is indicated by name in Figure 2.
- *'Base with Guide'*: Each component of this class has the fixed (none-moving) part of a guideway that can be either two rails or four carriages. If the fixed member is the NT_HST [see machines *a)*, *e)*, *i)* or *j)* in Figure 3] or the NT_TBL [see machine *b)*, *g)* or *h)* in Figure 3], then the fixed member has two guideways and is realised from two components of this class. If the fixed member is the HST [see machine *d)* in Figure 3] or the TBL [see machines *c)* or *f)* in Figure 3], then the fixed member has one guideway and one of the two components of the fixed member is realised from a component of this class.

4.2 Creation of Mutants

Some layout parameters describe the direction of the spindle, the direction of the table normal and the directions of the guideway normals. These directions are unsigned directions and can be specified with the drive directions of the three guideways, so that the user has to specify only parallelisms with the drive directions. Then the system generates (where it is possible) two opposed signed direction vectors for each unsigned directions. In this manner several so-called mutants can be created. Two or more similar machine tools are mutants if their unsigned directions are identical but at least one of the signed direction vectors differs in the sign of direction. Figure 5 demonstrates an example of machine tool mutants: for instance, the machine up and left and the machine down and left are mutants because they have opposed table normals; or the first and the second machines in the first row have opposed middle guideways.

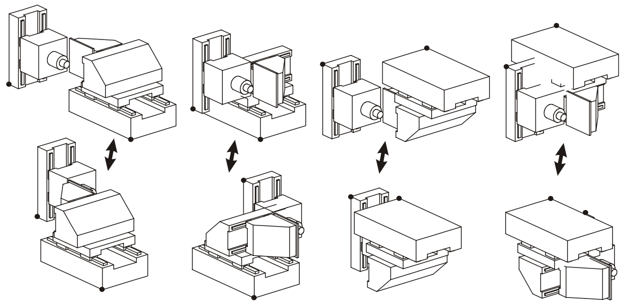

Figure 5. Example of mutants

4.3 Configuration of the Machine Tools

Many rules were defined to select the right components for the required machine tool layouts. These selection rules are determined by the layout parameters (some basic rules were already presented in Section 4.1). When the system assembles the components, a *complete parametric CAD model* for each machine tool layout is created automatically where the main dimensions of the components are derived from the workspace dimensions that are specified by the user. The parameterisation of the CAD models can be controlled by some input data. The configuration of the machine tool layouts can also be carried out without the assembly of the CAD models (see Section 5.2).

5. ANALYSIS

Six analysis tools were developed for the qualitative and quantitative evaluation of the synthesised machine tool layouts and their geometry.

5.1 Qualitative Analysis Tools

Qualitative analysis tools are in fact part of the configuration processes because they are applied to configure the machine tool layouts required by the user.

5.1.1 Validity Analysis

During the configuration processes some invalid layout variants might be created. The function of the validity analysis is to prevent the final configuration of such invalid variants. There are two types of invalid variants: rotated variants and unrealistic variants. A rotated variant is a rotated version of another variant, therefore one of the two is redundant. An unrealistic variant is a certain configuration of components that does not represent a workable machine tool. Such unrealistic variant would be created in a manner that the headstock and the table would turn into each other (in other words the spindle would point out of the table plane). Validity analysis comprises some spatial reasoning to verify if a variant is valid or invalid. Validity analysis is carried out during the creation of the mutants where the direction vectors alter their signs (see Section 4.2). From the current component library the system is able to generate *close to 68 thousand valid layout variants*.

5.1.2 Feasibility Analysis

The number of the valid variants is extremely large. Therefore, some *layout constraints* were introduced in order to restrict the layout variants of interest. A variant that satisfies the layout constraints is called *feasible variant*. Feasibility analysis encompasses some spatial reasoning to distinguish between feasible and infeasible variants. Several layout constraints and their corresponding feasibility analyses were developed. They are shortly presented below.

- *Elimination of Symmetric or Asymmetric Variants*: for example, machines *a)*, *b)*, *c)*, *f)*, *h)*, *i)* and *j)* in Figure 3 are symmetric, while machines *d)*, *e)* and *g)* are asymmetric.
- *Elimination of Mirrored Mutants*: Among the asymmetric mutants there are always mutant-pairs where the two mutants of a pair are mirrored versions of each other. For instance, in Figure 5 such mirrored mutant-pairs are connected by arrows. The system can eliminate one variant of each mutant-pair.
- *Constraining the Orientation of the Spindle and/or Table*: Some constraints were defined so that the resulting machine tool layouts have horizontal and/or vertical spindle and horizontal and/or vertical table. E.g., except machine *i)* in Figure 3 every machine has horizontal spindle; or except machine *d)* in Figure 3 every machine has horizontal table.
- *Elimination of Tilting Variants*: A variant is tilting if there is a horizontal guideway where the long part moves on the short part, or if there is a moving component that carries another horizontally moving component. For example, machines *b)*, *e)* and *h)* in Figure 3 are not tilting variants, while the other ones in this figure are tilting variants.
- *Elimination of Horizontal Fixed Guideways Facing Down*: This constraint was introduced because machine tools of such kind are difficult to build.
- *Elimination of Potentially Unrealistic Mutants*: Several constraints were introduced in order to filter machine tool layouts that are most probably unrealistic. These constraints are similar to the limitations of the validity analysis yet they are not so severe and can be switched on or off.

5.2 Enumeration Results

With the layout parameters and the layout constraints special groups of machine tools can be specified and the number of machines of these groups can be quickly enumerated, since the system is able to configure and examine the layout variants using the validity and feasibility analysis tools without assembling the CAD models. Some enumeration results are presented here as examples. The design system is able to generate 67,708 machine tool layouts of which 56,832 have solid headstock-chain and 10,876 have box-in-box headstock-chain. There are 8,960 symmetric and 47,872 asymmetric layouts with solid headstock-chain, and 2,970 symmetric and 7,906 asymmetric machines with box-in-box headstock-chain. There are 852 full box-in-box machines (i.e. the tables are fixed) of which 338 are symmetric. There are 20 full box-in-box machine tools that have coplanar guideways and their (fixed) tables are facing up. There exist 114 machine tools where the fixed members are the neighbour of the table (NT_TBL), the guideways are short-on-long and solid, the spindles are horizontal, the tables are horizontal and are facing upwards, and there are no mirrored mutants is this group.

5.3 Quantitative Analysis Tools

Four quantitative analysis tools were developed for the evaluation of the synthesised geometry of machine tools. To present them in detail is out of the scope of this paper.

- *Static Analysis*: It is the calculation of the displacements of the machine tool structures subject to static cutting forces. The measure of the static analysis is the displacement of the spindle relative to the table. The mechanical model of the structure is such that each guideway connection is assumed to be flexible and modelled by nine linear springs, and the bodies of the components are assumed to be rigid.

- *Dynamic Analysis*: It is the calculation of the first natural frequency of the machine tool structures. The mechanical model of the structure for the dynamic analysis is similar to that of the static analysis.
- *Interference Analysis*: It checks and calculates the geometric interference between the components of the assemblies. The measure of the interference analysis is the total volume of the interference objects.
- *Volume Analysis*: It is the calculation of the total volume of the components of the geometric models of the machine tools.

When using these analysis tools, the components can be in several positions on the guideways.

6. OPTIMISATION

6.1 Geometry Optimisation

The geometry optimisation is to optimise the CAD models of the machine tools synthesised by the system. During such an optimisation process the optimal values of some geometric parameters (e.g. dimensions) can be searched within given bounds. The optimisation criteria can consist of one or more of the following objectives: to minimise the static displacements; to maximise the first natural frequency; to minimise the geometric interferences; to minimise the total volume. A sequential quadratic programming algorithm was adopted and several *specific genetic algorithms* were developed to perform the optimisation tasks. In order to shorten the time of the optimisation processes, special *distributed computing* techniques were developed for the optimisation algorithms where the evaluation tasks are distributed amongst a network of computers. Figure 6 shows an example of the optimisation of six geometric parameters.

6.2 Layout Optimisation

During layout optimisations the optimal values of the layout parameters are searched for in a manner that the geometry of the machine tool described and synthesised by each layout parameter combination is also optimised. The objective function of the layout optimisation processes is the same function that was defined for the geometry optimisation. The layout constraints and the feasibility analysis provide means to constrain the design space in which the optimal values of the layout parameters are searched for. Therefore, the layout optimisations pose *constrained optimisation problems*. Two optimisation methods were developed. The first one is an *exhaustive search* where a limited number of machine tool layouts are

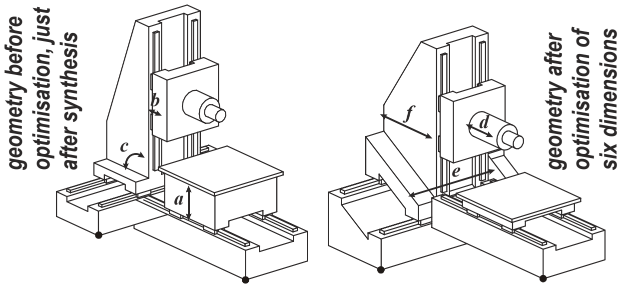

Figure 6. Example of geometry optimisation

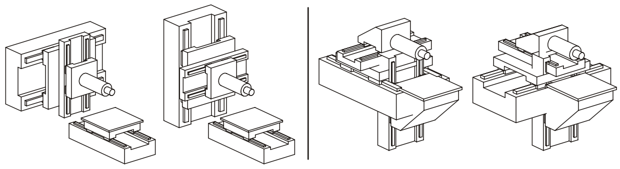

Figure 7. Example of layout optimisation

prescribed and synthesised, then the geometry of these layout variants are optimised, and finally the objective values of them are compared. The second method is a search with *genetic algorithms* where the layout parameters are coded in chromosomes and the layout constraints are included in the fitness values as penalty terms. Figure 7 demonstrates an example of the layout optimisation where the optimal layout of the 114 machine tools that were presented at the end of Section 5.2 was searched for: the left side of Figure 7 shows the best two layouts out of the 114; on the right of Figure 7 the worst two layouts are shown.

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