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DEVELOPMENT AND MANUFACTURING PROCESS OPTIMIZATION OF MECHATRONICS PRODUCTS BY INNOVATIVE KEY PERFORMANCE INDICATORS

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Abstract: The increasing complexity of mechatronics systems challenges both product- and production development. In this context, new methods have to be developed to support failure detection and -reduction by improving quality management and development processes. Innovative analysis methods show the capability to control process and reliability during the whole product life cycle by using key process/performance indicators (KPIs). As result of comprehensive analysis and evaluation, these metrics have to be introduced as soon as possible during product layout, development and manufacturing engineering. The present paper announces new approaches for process analysis and evaluation to support quality assessment and risk analysis during different stages of the life cycle of mechatronics systems.
Keywords: process optimization, quality management, key performance indicators, analysis methods

1. INTRODUCTION

Industry is faced with a continuously increasing complexity of products and rising customer demands for quality at the same time. With upcoming complexity, mechatronics systems are increasingly introduced into different types of products, e.g. in the automotive industry, infotainment devices and products related to the so-called internet of things. Developing mechatronics systems is quite a challenge because of different involved technical disciplines such as electrics/electronics (E/E), software and mechanics. Consequently, the development and production of these systems bear a high risk of possible malfunctions. In cases of faults occurring in customers' use, warranty leads to product recalls, which are typically associated with high costs. Thus, manufacturers and their suppliers have to ensure a continuous reduction of faults in their products. This can be enabled by improving both quality management and development processes, [1].

Innovative analysis methods may support control processes and reliability investigations during the whole product life cycle ensuring an effective quality management. Objective quality and process control can be enabled by a combination of analysis methods and key process/performance indicators (KPIs). KPIs are the result of comprehensive manufacturer-related analysis and have to be introduced as early as possible in the product development process, [1], [2], [3].

The development and production of complex systems always includes uncertain factors and residual risks that are influenced by increasing competition, shortened development durations, and cost pressure during all phases of the product life cycle. In that context, industry has the duty by law to ensure reliability of their products to prevent humans and environment from malfunction-cause damage, [1], [4], [5]. In an exemplary case of the automotive industry, recall rates have increased over the past years, which leads to additional costs for manufacturer and suppliers due to warranty, see Figure 1.

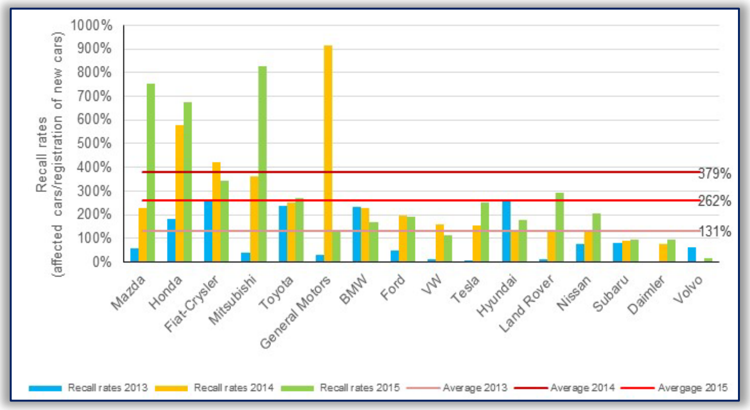

Figure 1 – Recall rates of exemplary automotive manufacturer in the US-market from 2013 to 2015, [1], c.f. [6].

State of the art quality management includes different types of tools, methods and processes that have been established during the past decades. With increasing share of mechatronics systems in modern products, these traditional quality management approaches are challenged in terms of insufficient suitability for description and investigation of mechanics, electrics/electronics and software. In this way, mechatronics products require new and innovative analysis methods to investigate their entire product life cycle effectively, [1]. The large amount of data and information available during product development and in-use-phases represents a key for innovative quality management approaches that will be discussed in this paper.

2. QUALITY MANAGEMENT

Quality-related issues affect basic product specifications, processes, measurements, and methods. These include functions of systems, reliability, support and service, resources management, design, warranty, and complaint management, [7]. Thus, quality represents a relative conformity of a system, process, or product with determined requirements and is connected to reliability representing the long-term quality behavior, [1].

Quality is an important issue to sustainable success and customer loyalty. Faults are always considered as decreased success of a company, increasing costs and bearing a risk of decreasing customer satisfaction. Thus, fault prevention is an important approach to provide quality and reduce costs. Quality and product characteristics are the result of the customer requirements specification and deliver quality checks, [7]. A fault represents the cause of a deviation and a potential failure within the system or product. Thus, faults are a non-fulfilment of requirements, e.g. non-fulfilment of customer requirements, quality or product characteristics, or process parameters that are outside of boundaries as well as badly performed tasks, [1].

In this way, quality represents the basis for successful products to satisfy requirements, enable customer loyalty, and ensure long-term success of companies. In practice it can be distinguished between different types of related quality, e.g. product quality (considering functional quality, long-term quality and service quality) and process quality (considering development, manufacturing and other processes), [1], [4], [8].

Development process related aspects

The development of innovative analysis methods helps to detect, evaluate and predict failures in mechatronics systems during all product life cycle phases, such as requirements definition phase, development phase, and use phase. Figure 2 shows relevant parts of a product life cycle, different types of failure occurrence and an overview of possible applications of enhanced quality management methods. The initial phase represents the "Requirement specification". Here, a comprehensive analysis method has to ensure that the specifications of mechatronics systems are analyzed and evaluated to detect possible system-related deviations and faults. This initial observation has to be performed on module and system level to enable preventive process planning and optimization. In the subsequent "Development" phase, analysis methods have to consider development- and test-data to enable an objective and comparable investigation of development processes. Key performance indicators represent an important supplement of well-established quality management tools for this section. Finally, the "Field" phase, meaning the use-phase at the consumers, delivers wide-ranging information for product improvement and product knowledge enhancement by use of customer feedback. A comparison and evaluation of both development data and field data can be supported by stochastic methods to create self-learning prognosis systems for the estimation of residual error rates, [1].

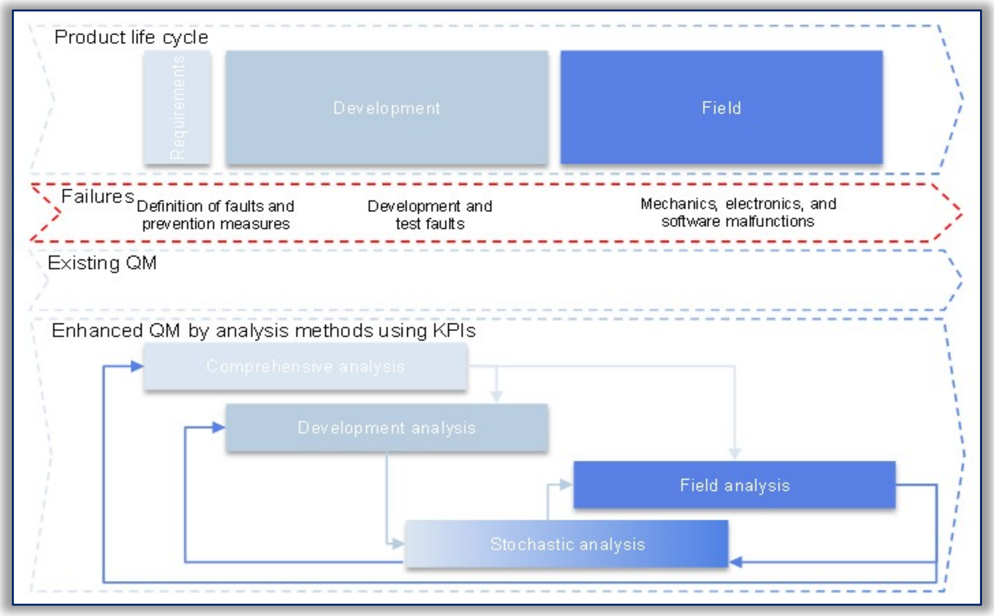

Figure 2 – Introducing new analysis methods into phases of product life cycle, [1], c.f. [2].

Different types of influencing aspects act on product quality management; they can be divided into internal and external factors. Customer-oriented aspects, e.g. society, employees, consumer behavior, shareholders, and legislation represent external factors. Internal factors include demands from different company in-house departments, e.g. production, development, finance, and sales. All these different aspects affect a broad area of product related processes, [1], [4], [8]:

- Protection planning
- Starting strategy
- Management of variants
- Commonality of series
- Component life cycle
- Continuous maintenance of products
- Market demand for innovative products
- Reaction on competition situation
- Optimization of contribution margin
- Legislation requirements
- Process and organizational structure
- Quality optimization

Reliability, availability, maintainability, and safety are characteristics with huge impact on costs and market acceptance. These influencing factors result in different requirements on the entire product life cycle, such as safety-relevant, reliability-relevant, economic, social, human, and environmental requirements. Changes in development always represent big challenges on processes and tasks. The increasing product maturity over development phases includes decreasing possibility of reaction to changes. These schedule-related effects always cause cost efforts that create unforeseeable additional impacts on development and management. Thus, changes concerning hardware components are often more challenging than software adaption, [1].

There are various standards and guidelines addressing different phases of product life cycle and quality management. General standards represent guidance and tools to ensure products meeting customer's and legislative requirements and high quality, e.g. ISO 9000 [8], ISO 9001 [9], ISO 9004 [10], ISO/TS 16949 [11], ISO/IEC 90003 [12], ISO/IEC 25000ff [13], ISO/IEC 15504 [14], ISO 26262 [15], VDI 2221 [16], VDI 2206 [17].

State of the art quality measures and tools

A continuous optimization of quality assurance during the entire product life cycle can be supported by two general strategies. Short-term quality measures include quick and target-oriented measures to restore product quality, primarily in case of safety-relevant systems that require immediate acts to avoid comprehensive recalls. In contrast to that, long-term measures by continuous quality improvement and stabilization are related to non-safety-related functions and characteristics. The optimization of quality in these areas supports the customer satisfaction and long-term business success. Preventive quality measures serve to improve quality and avoid weak points in advance. As part of the continuous quality improvement, drivers for this tasks are optimization measures due to competition, customer requirements, and complaints. Reactive quality measures treat faults and deviations that must be fixed as soon as possible depending on their criticality. Continuous knowledge building and evaluation of faults are very important tasks for reactive measures. During development, both product effectivity to fulfil customers' requirements by optimizing product value and product efficiency to ensure a customer-related realization by controlling cost drivers have to be considered. A customer-related development uses traceability, testing strategy, and fault diagnostics, [1].

Today's quality management uses different methods and tools to ensure quality considering prescribed approaches, preventive use, various effects and development phases. State of the art are methods and tools reaching from abstract approaches to precisely defined guidelines [19].

Problem solving methods are applied, if quality management detects a deviation to define the reason for a problem and solve the problem (such as the general problem solving approach). This approach includes target determination with boundary conditions, problem analysis as well as description of the fault/detecting and cause research, finding of solutions with research and evaluation, measures implementation, and standardization. Different tools are used to improve quality in a company, such as flow charts, fault collecting cards, histograms, pare-to analysis, correlation diagrams, Ishikawa diagram, and traffic light charts, [1].

- *Quality Function Deployment (QFD)* is a systemic quality planning method using customer orientation. "What" expects the customer and "how" are requirements fulfilled? These consideration results in a relationship matrix, the so-called House of Quality, [1].
- The *Failure Mode and Effects Analysis (FMEA)* is a common qualitative analysis method and often used in industrial applications. This method enables an investigation of failure modes, their causes and consequences. Furthermore, the FMEA delivers an evaluation of failure-related risks. The reliability

investigation delivers the so-called risk priority number (RPN), which is the product of the three parameters severity (S), occurrence (O), and probability of detection (P), [21], [22], [23].

- *Fault Tree Analysis (FTA)* is also a common reliability analysis method that enables a qualitative and quantitative top down approach. FTA starts on the basis of a specific failure or breakdown, representing the primary event and evaluates different functions by use of Boolean Operators to investigate their connections and the basis cause event, [21], [22], [23].
- *Statistical Process Control (SPC)* delivers evaluation and control by use of quality regulation cards under consideration of the fact, that production environment and circumstances are changing throughout the production timeline. This method highlights small fault rates, detects deviations, enables controllable processes, uses representative random samples and enables statistical safeness, [24].
- *Poka-Yoke* was developed for the Toyota production system and influences various processes based on an assumption of a zero-fault-strategy. Even if zero faults are not realistic, this method interprets a non-zero-fault strategy as expectance of faults. This method uses an approach that eliminates random failures during production process, because human failures are natural and cannot be avoided in principal. Poka means random unintentional failure and Yoka means avoidance or reduction, [1], [25].
- *Total Quality Management (TQM)* is an approach that ensures quality in a company by including internal and external customers, processing improvement, developing quality in the organization, and developing a measurement analysis program. The idea is that everyone in the organization is both customer and supplier. The main target is to reach customer needs and quality expectations by a holistic approach to enable all functions of the organization following high quality standards. TQM considers all areas within the company by identifying zones for improvement, [1], [26].
- *Stochastic quality methods* can be applied to support the above-mentioned approaches and to bring in enlarged possibilities. During production, system characteristics scatter due to various circumstances, such as systematic deviations (e.g. wear out effects). Hence, quality management uses a definition of boundaries to control production processes, [1], [27]. Various stochastic analysis methods use descriptive statistics, quantitative characteristics, medians, variances, and distributions.

3. INTRODUCTION OF KEY PERFORMANCE INDICATORS

The traditional quality management methods and tools described above come to their functional borders in case of complex mechatronics products. This is based on the fact, that mechatronics products include three disciplines: mechanics, electrics/electronics and software. The close integration of these different technical areas leads to complex behavior in terms of quality-related aspects. In this way, the traditional quality management methods have to be enhanced by new approaches. As one potential supplement, so-called key performance indicators (KPI) are able to control and monitor the development process and even the entire product life cycle of mechatronics systems. KPIs base on metrics, which are related to quantitative and qualitative information that is used to evaluate the fulfillment of aims and goals of a company. In general, specific analysis methods have to be applied to define KPIs. In this context, four types of parameters can be differed, [1], [2], [28], [29], [30], [31]:

- » Critical Success Factors (CSF)
- » Key Result Indicators (KRI)
- » Performance Indicators (PI)
- » Key Performance Indicators (KPI)

Depending on company-related preferences, values and target, different indicators are able to deliver the suitable information and statements. During the first step of the KPI definition process, the mission, vision, and important values have to be defined to specify Critical Success Factors (CSF). There are three types of indicators: Key Result Indicators (KRI), Performance Indicators (PI), and Key Performance Indicators (KPI). Figure 3 shows the relationship between these three types of performance- and progress-related metrics. The indicators are used simultaneously, but deliver different statements. KRI represent the outside layer as so-called overall conditions. PI are represented as various indicators within different layers under outside skin. Finally, KPI represent the core of the process and progress performance in the middle circle, [1], [28], [31].

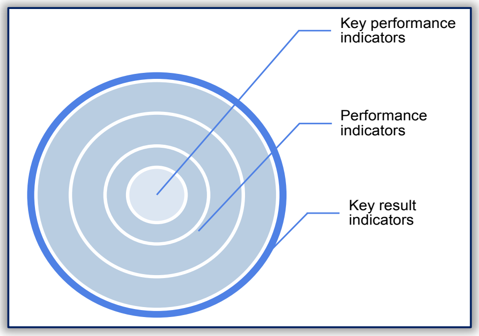

Figure 3 – Relationship of indicators, [1]

As representatives of business success, *Critical Success Factors (CSF)* answer the question "What has to be done to be successful?" (E.g. to increase quality, to attract new customers). Hence, CSF are crucial determinations to ensure the success of a company or a large project. Various objectives include basics for the definition process of CSF to ensure an efficient and successful strategic management. For instance, defining CSF uses practical logic, heuristics, or rule of thumb by brainstorming rather than elaborating procedure or theoretical models. Additionally, managerial experience over the years supports decision-making based on CSF as well as the analysis process based on expert statements and past organizational success. CSF enable a distinction of successful and not successful companies as well as the definition of key point areas to determine objectives and devising measurements of performance. CSFs and KPIs are interacting as effects of a company's tasks and performance, [1], [28], [31], [32].

Key Result Indicators (KRI) deliver information about how the project or progress is done. These indicators are used to define if the process or project heads towards the right direction. KRI enable monitoring through-out a longer time period and include monthly or quarterly information sampling, such as, [1], [28], [31]:

- » Customer satisfaction
- » Profitability
- » Employee satisfaction
- » Net profit before tax
- » Return on capital employed

Performance Indicators (PI) give information about what to do in a project. They include various parameters between KRI and KPI, for instance, [1], [28], [31]:

- » Process time
- » Ratios
- » Various metrics
- » Profitability of the top 10% of customers
- » Net profit on key product lines
- » Percentage increase in sales with top 10% of customers
- » Number of employees participating in the suggestion scheme

Finally, *Key Performance Indicators (KPI)* deliver information about how to increase performance. They are represented by a set of parameters, which symbolize the most important measures for the current and future success (e.g. the residual error rate or the fulfilment degree of requirements). KPI are permanently applied for analysis of the daily or weekly progress and performance during the whole product life cycle in general, but especially during development phases. These indicators are important measurements to avoid risks and complications at the end of development or at least at the customer stage. Nevertheless, the generated information represents the basis to develop statements about necessary actions. KPI are objective, quantitative measurements to handle CSF enabling control of status, progress, and performance trends. The combination of CSF, which are requirements to reach a business target, and KPI as quantitative measures for the achievement of long-term targets, enables an efficient project control and even the support of company-success-related issues. With the target to connect KPI to business strategies and quality management, efficient and effective analysis methods are required. For this purpose, the following objectives have to be considered for the determination of KPI, [1], [27], [30]:

A *Consideration of partnerships* (e.g. to suppliers, customers or unions) is important for uniform communication and transparent decision-making. Thus, all stakeholders have to be informed and have to be considered if changes are required. In addition, a common development strategy, involvement of suppliers and customers, as well as the status of progress of implementation should be considered.

Transfer of power to the front line represents an important precondition for successful performance and process improvement. Effective communications, enabling KPI handling, sensitization for understanding of KPI and CSF, as well as the definition of responsibility of teams are efficient ways to transfer the power.

Implementation and integration of reporting, measurement, and improvement of performance supports efficient and focused decisions, which are required for the enforcement of iterative, time-depended processes of developing strategies to generate performance measurement and improve productivity.

Essential for success is a close *connection of KPI to strategy*. In this way, KPI should be linked to strategy-related aspects, following the process of indicator definition, as shown in Figure 3. This connection of indicators to the mission, vision, and values of a company, respectively project deliver efficient measurement or evaluation possibilities, [1]. In general, KPI are characterized by the following characteristics, [1], [7]:

- » KPI describe the process due to effectivity, efficiency, and quality.
- » KPI detect deviations and changes in processes.
- » KPI are measurable and objective.
- » KPI have a target value (part of the company's target).

» Reaching KPI targets equals reaching company's targets.
» The defined set of KPI has to be consistent to the company's targets.

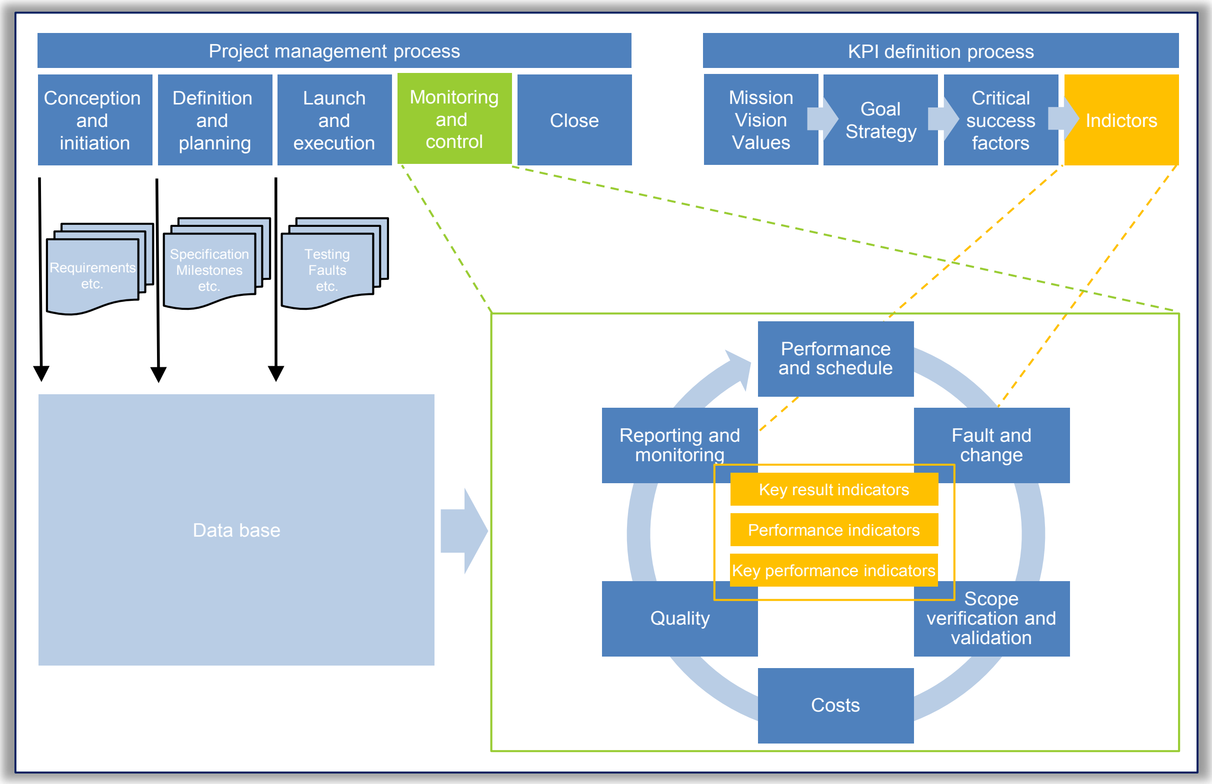

Figure 4 – Principle approach of generating KPI on basis of development and test data, [1], c.f. [6]

During the whole project management process, the basis for enhanced analysis is collecting data and information, such as requirements, system- and components-specifications, tests, faults, and milestones. Thus, a database should be used to store and connect development as well as test data to provide a prepared analysis platform. To enable suitable statements, the KPI definition process has to be performed by considering various parties, views and needs during development processes. KPI support investigations of performance and schedule, fault and change, costs, quality, as well as reporting and monitoring. Different types of perspectives are included, e.g. management, project management, quality assurance, and process management (Figure 4). Development processes use different items to handle process and progress. Hence, requirements are usually a result of project specification serving for communication between customer and supplier, [1].

Due to various development phases and project maturity, specific KPIs delivered by differently developed analysis methods enable control during every step. Examples for quality-related aspects that can be evaluated by use of KPI are, [1], [28]:

- *Status and progress* are applied to check the actual projects status, tasks, and progresses by descriptive statistics.
- *Durations* allow the investigation of all kind of processing periods.
- *Tracking* supports control of data quality and progress management by checking target and performance as well as linkages between items on subcomponent or module level.
- *Target-performance comparison* enables an association of target and performance as well as an investigation of deviations in development processes.
- *Fault estimation* supports evaluation of detected and fixed faults over the project maturity or time lane.
- *Trend analysis* supports the understanding of development processes and evaluation of tendencies of performance or progress.
- *Prediction* enables the estimation of the residual error and checking the trend of faults during development. Furthermore, release decisions are supported by delivering statements of possible faults remaining in the system at certain release points.

5. CONCLUSIONS

Increasing complexity of mechatronics products challenges development processes, production engineering and quality management because of the complex integration and interaction of software, electrics/electronics

(E/E) and mechanical components. The manifold technical properties and difficult relations of mechatronics systems in diverse industrial applications require innovative analysis and evaluation methods throughout the entire product lifecycle to provide reliable and safety products.

Besides an application of well-established quality management tools, new approaches need to be implemented to scope with the increasing product complexity. The present publication introduces a guideline for the development and implementation of Key Performance Indicators (KPI) and discusses possible considerations of influencing factors. The creation of indicators is closely related to the company structure and the actual product. In this way, the KPI-definition process requires a deep analysis of existing structures, development processes and production procedures to find objective, quantitative metrics. A precise evaluation of development data, information from production and potentially data from product use in customer hands provides the basis for comprehensive analysis of possible sources for weaknesses. Target is the generation of deep understanding of quality-related factors in development and production processes as well as knowledge about the product behavior in customer usage. This know-how can be extracted to define key values for the improvement of existing processes and the development of new approaches to face the high quality demands of complex mechatronics systems.

Note

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