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Technological process planning focused on complex manufacturing processes of the digital era

Roman Wdowik[a]*, R.M. Chandima Ratnayake[b], Marek Magdziak[a], Artur Bełzo[a]

[a]*Ignacy Łukasiewicz Rzeszów University of Technology, The Faculty of Mechanical Engineering and Aeronautics, al. Powstańców Warszawy 12, Rzeszów 35-959, Poland*

[a]*University of Stavanger, The Department of Mechanical and Structural Engineering and Material Science, N-4036 Stavanger, Norway*

* Corresponding author. Tel.: +48 17 865 11 32; fax: +48 17 854 25 95. *E-mail address:* rwdowik@prz.edu.pl

Abstract

The paper concerns the planning of complex technological processes (CTP). Nowadays, CTP are gaining new meaning in manufacturing environments. This is due to the increased number of innovative solutions having a crucial impact on the effectiveness of production. CTP can be defined as manufacturing approaches which are a blend of the traditional and verified manufacturing processes (TPs), such as traditional cutting, grinding or electro discharge machining, with modern technologies (emerging technologies, also known as complex processes (CPs)), which are under constant development, such as hybrid machining, 3D printing, micro and nanomachining, etc. The application of CPs in the process chain requires a calculation of risk and is usually acceptable in developed firms. Various research centers are looking for new applications of CPs and intensively studying their performance. New machine constructions, tools, manufacturing strategies and digital tools (DTs) are inter alia studied. As a result, some of the abovementioned developments reveal new perspectives for production performance. The paper discusses the role and place of these modern manufacturing techniques in CTP structures. It also points to and discusses a risk and reliability analysis. Moreover, teaching methodologies in the area of CTP are indicated, in order to formulate the proper approach of engineers within the CPs' implementation phase. In this context, CTP may be supported by the use of digital tools (e.g. software tools).

Keywords: process planning; complex; manufacturing; digitalization

1. Introduction

Today, manufacturing and mechanical engineering research is focused on an increase in effectiveness (i.e. cost reduction), hybridization, customization and digitalization[1-3]. Production plants develop their technological processes by testing and implementing many emerging technologies. This reveals the complexity of production methodologies and causes a complexity of process chains. In this context, complex technological processes (CTP) are becoming more popular nowadays. They can be defined as manufacturing approaches which are a blend of the traditional manufacturing techniques (e.g. traditional cutting, grinding or electro discharge machining) with modern technologies which are under constant development, such as hybrid machining, 3D printing, micro and nanomachining, biomachining, etc. In other words, CTP are a combination of traditional processes (TPs) and complex processes (CPs).

In the economic battle between different producers, the quality of manufactured parts, their fast accessibility for the final customer, customization and customerization [4] to the customers' expectations, as well as the price of manufactured products, play a crucial role for both manufacturers and the final customers. Producers of machine tools deliver new manufacturing techniques to manufacturing environments, in order to fulfill the actual requirements of production. However, there is a need for development regarding the planning of technological processes while changes in manufacturing

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environments have become more frequent, due to the digitalization and fast development of new technologies. Accessibility to various goods is one important factor which decides development. Unfortunately, existing process planning methodologies, including digital tools such as CAD/CAM/CAPP tools, are usually not designed to meet the requirements of CTP. They are only adapted to well-known manufacturing techniques (TPs), due to the much greater potential for a fast sale.

In this context, in the early stage of CPs' existence, process planners usually use only their experience and limited research results, to implement CPs in process structures and develop process parameters, etc. This is a reason for research into the new methodologies and approaches regarding CTP in the digital era of manufacturing, which is subject to rapid change.

2. Discussion on the general structure of the CTP

The traditional technological process regarding mechanical machining (TTP) consists of a set of technological operations (TOs) which are run using designed physical workstations (e.g. machine tools, robotized manufacturing cells, etc.) [5, 6]. In the case of such process types, TOs concern traditional processes, which have been well-known in industry and verified by a large number of entrepreneurs. Widespread technologies, such as turning, milling, welding or electro discharge machining, can be assigned to the TPs.

Implementing the newest technologies in the structures of technological processes leads to a combination of TPs and emerging manufacturing techniques (EMT), which, within the paper, are named complex processes (CPs). Today, there are numerous examples of the abovementioned CPs, such as hybrid processes, 3D printing or micro and nano technologies, biomachining, etc. They are currently under development, and a lot of research gaps still exist. This justifies their complexity. These new technologies may be mixed (combined) with the verified, well-known technologies (TPs), in order to achieve the same or similar products within a changed process chain. This "combination" should lead to the proper and successful manufacturing of final products. If CPs are involved, process planning is not the same as in the case of TPs. It may also be stated that some of the abovementioned CPs, which are the real innovations, have the potential to replace the previous TPs in future manufacturing environments. Moreover, CTP will not become a traditional process unless the new procedures are commonly used by firms. In this context, complex technological processes (CTP) exist until CPs require improvements and wide understanding in the manufacturing process chain. Fig. 1 presents the graphical interpretation of TTP and CTP structures. CPs may be placed differently within the CTP chain, and their number must be greater than or equal to 1. Fig. 2 illustrates exemplary manufacturing techniques which are included in TTP and CTP. CTP may also consist only and exclusively of CPs.

The abovementioned explanation is necessary, in order to identify the most important notions used within this work. It also tentatively presents the need for research focused on complex technological processes. The analysis of complex and traditional processes indicates the need for change in the CTP methodology, risk analysis, process reliability analysis, etc. It also indicates that the content of training and courses for students and engineers should be updated.

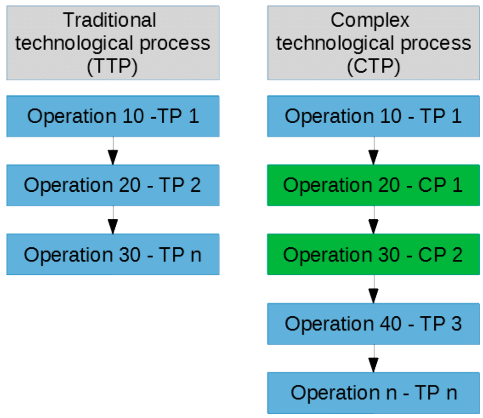

Fig. 1. The difference between traditional technological processes (TTP) and complex technological processes (CTP), on the basis of example process structures.

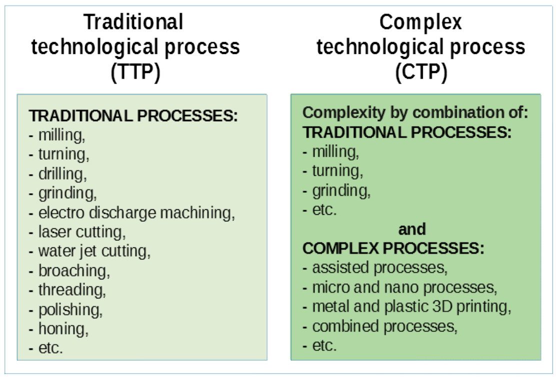

Fig. 2. Examples of manufacturing processes included in traditional and complex technological processes.

3. Risk assessment in the CTP

The proper implementation of modern manufacturing techniques in the process chain requires the analysis of verification criteria (see Fig. 3) which play a crucial role in the decisions of process planners. Verification of the reasonableness of the CTP is supported by the extended analysis of price (e.g. possibility of cost reduction), total process time (e.g. opportunity to reduce total time), quality of manufactured part (e.g. less surface roughness, higher accuracy, etc.) and safety of process and operator (e.g. safer working conditions, verified process monitoring techniques). The CPs' application in the CTP should support selected (at least one) or all the abovementioned verification criteria. Otherwise, the CTP are not useful and should not be applied in manufacturing environments. However, traditional processes may meet all the necessary requirements of technological planning and the final customer.

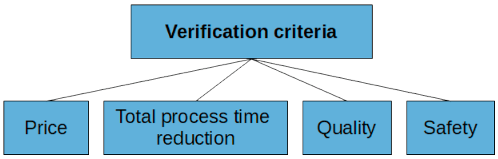

Fig. 3. Criteria of CP/TP usefulness.

The tentative confirmation of the importance and usefulness of CTP through the analysis of verification criteria should be confirmed by a detailed risk assessment analysis, together with reliability analysis of the CTP.

The complexity of CTP causes an increased risk, which is the main factor influencing the necessity of the final implementation of a complex process. Fig. 4 presents a comparison of TTP and CTP which may be used within a risk assessment, taking into account the drawbacks of CTP compared to TTP. On the basis of the presented comparison, it may be stated that the risk level in the case of a complex process is always higher compared to that of a traditional process. This is due to the lack of extended knowledge and experience regarding machines, the need for additional training in the area of new technology for process planners, and other limitations, such as a small number of spare parts or service providers. On the other hand, traditional processes are characterized by a relatively large number of machines in the market, existing guidelines, etc.

Hence, the final decision regarding the implementation of CPs in a manufacturing environment should be made after an extended risk analysis. Manufacturing firms can make a decision if the following issues are solved:

- The access to research results concerning CPs is obtained
- The other users (other companies) of CPs are surveyed by qualified staff
- Tentative tests are completed

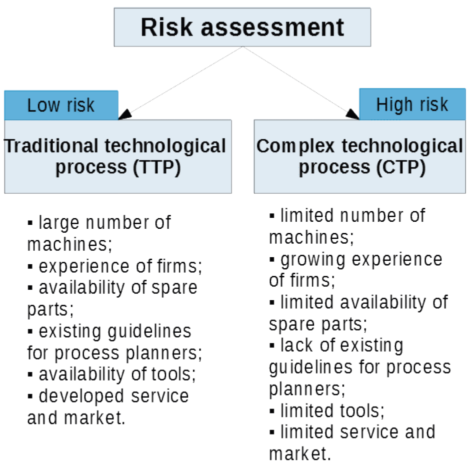

Fig. 4. Challenges of risk assessment for traditional and complex technological processes.

Fig. 5 presents the stages of production in which the process of verifying CTP usefulness may be performed. It is important to indicate that the verification process may be realized at the beginning of the planning of a whole technological process or after the completion of some operations. The verification process should be based on verification criteria and run by the use of a verification algorithm. The same approach may be used in risk assessment. However, verification criteria analysis should be performed prior to risk assessment.

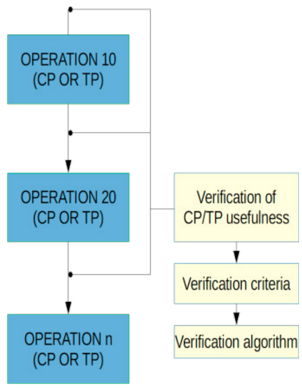

Fig. 5. The decision-making process regarding the use of CP or TP in the process chain.

4. Complex technological processes as reliability systems

The implementation of complex processes into the process structure has a great impact on the entire technological process reliability (TPR). The TPR is defined as the possibility of concurrent exploitation of machines responsible for the realization of both traditional and complex technological operations, building one complex technological process structure (refer to Fig. 1).

The exploitation of machines involves many aspects, such as construction, operation, maintenance, exploitation conditions, etc. All these aspects related to separate technological operations have an impact on the total reliability. Manufacturing systems which are susceptible to rapid damage are characterized by lower reliability than durable systems. In this context, newly developed CPs, which may be classified as sub-systems, exist in complex technological processes and are supposed to be vulnerable to failure, mainly if there is limited knowledge from their exploitation process. However, the reliability of such systems cannot be defined on the basis of single process replication.

The CTP (but also the TTP) may be considered as a series of reliability systems (see Fig. 6) having a defined number of sub-systems. Hence, CTP consist of TPs (TP operations) and CPs (CP operations). However, at least one CP operation is required. The general assumption regarding the reliability of such systems may also be defined:

$$R_{co} < min\, R_{to} \quad (1)$$

This means that the reliability of every complex process (R_{co}) in the technological process chain is lower than the lowest reliability of a traditional process (R_{to}) existing in the technological process chain. The abovementioned Equation (1) may be considered a reliability-related definition of the CTP. Fig. 7 presents how TPs and CPs may be designed in technological processes, in order to prevent unexpected failures and increase the total process reliability. A parallel sub-system existing within the entire process plan may decrease the risk of failure at the early stage of CP implementation. At the same time, the costs of CTP may be increased by additional preparatory activities. If the knowledge regarding realization of involved CPs is extended, the reserve parallel structure may be simplified, and existing TPs in the sub-system may be removed.

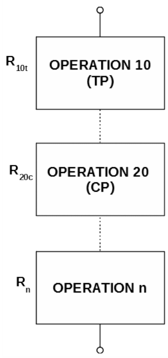

Fig. 6. CTP as reliability system.

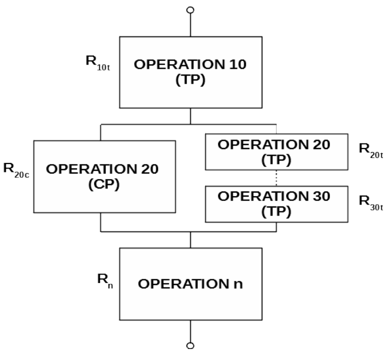

Fig. 7. Shaping the reliability of technological process by the use of TPs and/or CPs.

Finally, in conclusion, the technological process reliability (R_s) depends on the reliability of every technological operation within the process – both traditional (e.g. R_{10t}) and complex (e.g. R_{20c}) (see Eq. (2)). However, the reliability of traditional operations (processes) R_{to} and the reliability of complex processes R_{co} may be calculated separately, according to Eqs. (3), (4) and (5). The reliability of one technological operation may be classified as the probability of its successful completion, if it is run the defined (specified) number of times and by the use of the same machines and equipment. The technological operation is successfully completed if all the requirements defined by a process planner are obtained.

$$R_s = R_{10t} * R_{20c} * \dots * R_n \tag{2}$$

$$R_s = R_{to} * R_{co} \tag{3}$$

$$R_{to} = R_{t1} * R_{t2} * \dots * R_{tn} \tag{4}$$

$$\mathrm{R_{co}} = \mathrm{R_{c1}} * \mathrm{R_{c2}} * \dots * \mathrm{R_{cn}} \tag{5}$$

The R_s depends not only on the technological equipment and hardware reliability which is used but also on software reliability, accounting reliability and operational reliability (see Fig. 8). The CPs included in the process plans may cause failures due to technological equipment failures, which can be indicated as the main and the most important element of technological operation reliability. This is mainly caused by limited experience regarding the involved CPs. However, in the authors' opinion, other elements, such as software reliability, accounting reliability, and operational reliability, are also important, but their impact on R_{co} requires further research.

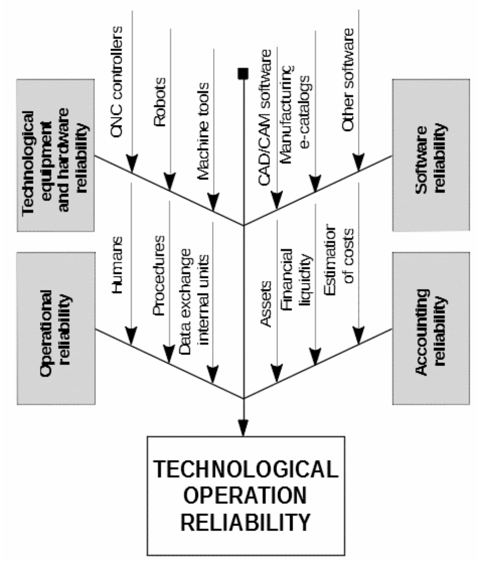

Fig. 8. The fundamental parts of technological operation reliability in the case of TPs and CPs.

5. Digital tools in the CTP

The use of digital tools in the case of complex technological processes may help in the acceleration of transformations from CTP to TTP. The main focus should be on software tools. Today, limited software tools support complex processes, and a majority of solutions are focused on TP. For example, typical CAD/CAM software supports many traditional technologies, such as turning (Fig. 9a) or milling (Fig. 9b). Some, but not many, combined processes, such as turning and milling, using one machine tool are also supported (Fig. 9c) The application of digital tools is presented in Fig. 9 and Table 1 as a typical technological process designed by the use of CAD/CAM software. In some cases, combined processes (Fig. 9c) may also be classified as CPs because the knowledge about their proper application is still under development.

If emerging technologies (e.g. laser assistance) are added to the process, there is no available CAD/CAM software which could support the planning of the entire technological process, even if some parts of the process (e.g. tool paths) can be successfully developed. For instance, there is no laser-assisted process simulation in CAD/CAM software.

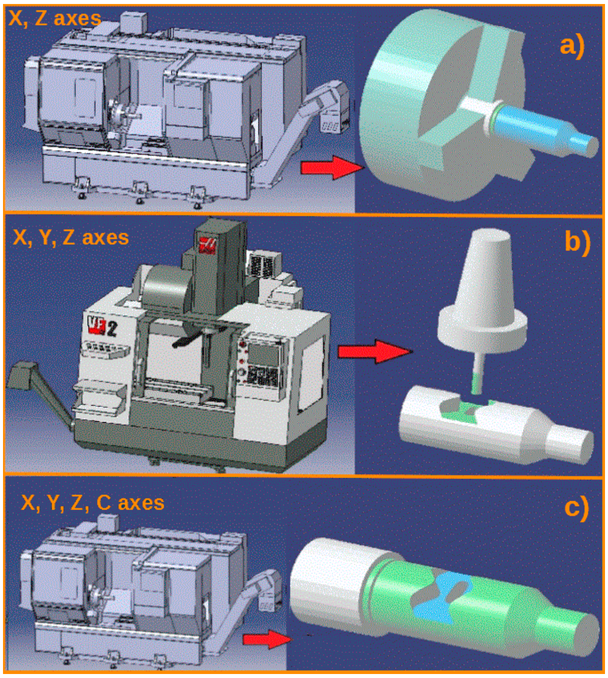

Fig. 9. TTP vs. combined process (turning + milling): a) turning using lathe, b) milling, c) combined turning + milling using one machine tool.

Table 1. Exemplary order of tasks and machining parameters used in CAD/CAM Catia software

	Name of machining tasks	Machining parameters			
		v_c (velocity of cutting) [m/min]	f (federate) [mm/rev]	a_p (axial depth of cut) [mm]	a_e (radial depth of cut) [mm]
Lathe	1. Rough turning	150	0.2	1	
	2. Profile finish turning	170	0.2	0.2	-
	3. Groove turning	150	0.2	2	
Milling machine tool	1. Pocketing	170	0.22	0.4	0.7
	2. Pocketing finish	200	0.22	0.8	0.2
	3. Profile contouring	200	0.22	0.8	0.2
Multi-turn machine tool	1. Rough turning	150	0.2	1	-
	2. Profile finish turning	170	0.2	0.2	-
	3. Pocketing	170	0.22	0.4	0.7
	4. Pocketing finish	200	0.22	0.8	0.2
	5. Profile contouring	200	0.22	0.8	0.2
	6. Groove turning	150	0.2	2	-

6. Complex technological processes: from the perspective of the teaching process and the use of digital tools

Teaching complex technological processes mainly concerns the process design phase (see Fig. 10), which precedes the main manufacturing phase as a necessary element of the production process. The proper implementation of complex processes in manufacturing environments requires up-to-date knowledge dissemination on the basis of recent scientific achievements. In this context, students should be familiarized with a presentation of CTP benefits and comparisons of the TTP and the CTP, which lead to the same manufacturing aims by manufacturing similar products. Students should also be involved in testing/verification regarding the usefulness of various digital tools (such as software or devices) in planning activities regarding complex technological processes. Unfortunately, currently there are no customized digital tools which can fully support the planning of complex processes. However, TPs' operations are supported by a wide range of CAD/CAM software, and new products have been developed for selected CPs (e.g. modules for additive manufacturing in Siemens NX software). In the case of TPs, planning activities do not require advanced research activities because general knowledge about these processes exists. On the other hand, CPs have not been fully researched. In the authors' opinion, in the case of CPs, the teaching process should focus on the digital tools which enable research activities, such as DOE software, rather than on the use of typical CAD/CAM/CAPP software tools.

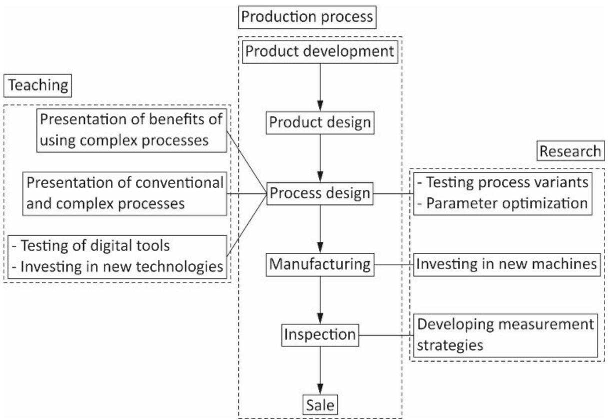

Fig. 10. The scope of CTP teaching.

7. Conclusion

As presented in this manuscript, technological process planning for complex processes reveals many challenges regarding the order of processes, risk calculation, expenditure regarding process implementation, application of digital tools, etc. We have developed new terminology, presented risk-related issues in complex technological processes and the reliability of such processes. Reliability-related definition of complex technological process have been proposed. This definition can be used on the basis of the results of experiments focused on traditional and complex processes existing in process chain. However, important reliability parts (presented in Fig. 8) should be considered and defined for the aims of experiments. Also, the final definition which process and technological operation is a complex one can be proposed if the minimal reliability value is defined. Distinguishing between TPs and CPs is possible by the use of reliability values.

We have also indicated selected teaching concepts because we observe that complex processes are thought without paying attention of the limited knowledge in this area (e.g. the use of DOE software should be discussed in the case of CTP teaching). New research areas, such as the detailed analysis of risk, are suggested for future work.

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