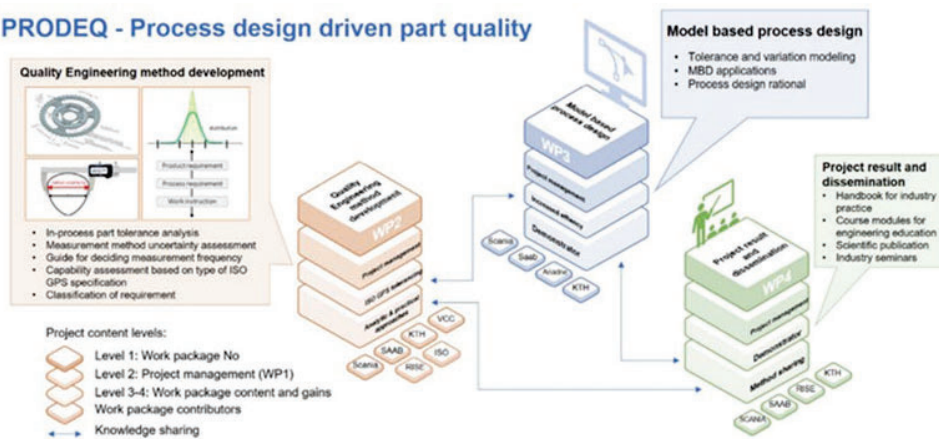


PRODEQ – Process design driven part quality

Public report

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Project within **Sustainable production**
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 Date **20260410**



Fondonsstrategisk
 Forskning och
 Innovation

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FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

Process and quality planning is a cross-organizational activity essential for achieving high product quality at competitive cost. It focuses on designing manufacturing processes where each operation fulfills a specific function to transform raw material into a finished product. The project aimed to strengthen process planning by developing methods and tools for quality-driven process design. Key focus areas included in-process tolerance chain analysis, assessment of measurement method uncertainty, and capturing design rationale using Model-Based Definition (MBD). Main objectives have been to improve measurement and control strategies to reduce variation and handle tighter tolerances, clarify requirement interpretation to ensure consistent quality across production sites, enhance in-process requirement design for faster optimization and flexible production, standardize work methods to reduce duplication and establish best practices. Fulfilment of these objectives were expected to contribute to faster product introduction and better manufacturability through early integration of production considerations, stronger quality control by linking requirements to product and process functions, more efficient measurement strategies, and new process evaluation methods. The project has examined tolerance stack-up caused by clamping variations in multistage machining in a novel way where tolerance stack-up analysis software has been used to simulate clamping errors. The simulations were followed by physical experiments on a machining center confirmed how operator-dependent clamping variations influence final part geometry. Another major contribution was the development of structured methods for assessing measurement method uncertainty within the ISO GPS framework. Test specimens with controlled form deviations were used to evaluate how different measurement methods influence results. The study showed that uncertainty depends heavily on part geometry and measurement technique. The outcome formalized long-used industrial practices and enabled better process control, simplified measurement strategies, and improved tolerance handling. A significant project result is the publishing of the international standard ISO 24096 Technical product documentation (TPD) — Classification of requirements, which provides a framework for requirements classification. In the domain of process design and capturing of process design rationale the project partner Scania has developed a methodology using a “criticality index” (CI) to evaluate manufacturing features based on design and process factors such as tolerances, complexity, machine performance, and tooling. Project results have been integrated into engineering education (e.g., at KTH), and disseminated at industry workshops, conferences and within the community of international standardization.

Despite some challenges, the project has delivered valuable advancements in process and quality planning. It has established some methods for structured, standardized approaches for process design, measurement, and requirement classification. The results are expected to support future development of AI-driven engineering tools, enabling faster development cycles, improved collaboration, and higher product quality.

2. Sammanfattning på svenska

Syftet med projektet har varit att stärka process- och kvalitetsplanering genom att utveckla metoder och verktyg för integrerad kvalitetsdriven processdesign. Detta eftersom det är en tvärorganisatorisk aktivitet som är avgörande för att uppnå hög produktkvalitet till konkurrenskraftig kostnad. Projektet har också lyft fram det viktiga perspektivet att artikelberedning är en designaktivitet vars målsättning är att utforma tillverkningsprocesser där varje operation fyller en specifik funktion för att omvandla ett råmaterial till en färdig produkt. Målsättningen har varit att förbättra mät- och styrstrategier för att minska variation och hantera snävare toleranser, tydliggöra tolkningen av krav för att säkerställa enhetlig kvalitet mellan produktionsenheter, förbättra utformningen av processrelaterade krav för snabbare optimering och flexibel produktion, samt standardisering av arbetsmetoder för att minska dubbelarbete och etablera bästa praxis. Viktiga fokusområden har varit att testa och utvärdera metodik för toleranskedjeanalys vid omspanning av arbetsstycken och att simulera hur variation vid omspanning påverkar slutresultatet. Publicering av den internationella standarden ISO 24096 Teknisk produktdokumentation (TPD) – Klassificering av krav, är ett betydande resultat från projektet. Ett annat intressant resultat inom området processdesign och dokumentation av design rational är en metodik för att utvärdera tillverkningsdetaljer som utvecklats inom projektet av Scania. Metoden använder ett "kritikalitetsindex" (CI) för att utvärdera tillverkningsdetaljer utifrån design- och processfaktorer såsom toleranser, komplexitet, processer, tolerans- och referensrelationer, maskin- och verktygsprestanda m.m. Utöver att ha presenterats vid interna workshops i projektet, branschkonferenser och internationellt standardiseringsarbete, har projektresultaten framför allt integrerats i ingenjörsutbildning vid KTH. Trots vissa utmaningar har projektet levererat värdefulla bidrag inom process- och kvalitetsplanering genom att etablera metoder för strukturerat och standardiserat arbetssätt vid utformning av processer, mätning och geometrisäkring samt kravklassificering. Resultaten har stor potential till att bidra till utvecklingen av framtida AI-baserade ingenjörswerktyg för kollaborativ process- och kvalitetsplanering som kan möjliggöra kortare utvecklingscykler, förbättrat samarbete och högre produktkvalitet.

3. Background

Process- and quality planning is a cross-organizational process and a prerequisite to produce products with intended quality at competitive cost. Product quality is achieved through careful design of the manufacturing process in which every single operation has a purpose in the sense of performing an intended function. Here, process planning has a critical role as responsible for developing and communicating the functions required to transform a blank into a product with intended quality.

4. Purpose, research questions and method

The aim of the project was to strengthen process planning methods and tools by developing methods for process design driven part quality, particularly development of new engineering work methods for in-process part tolerance chain analysis and measurement method uncertainty assessment. Process design rationale, usually driven by engineer's tacit knowledge, have been of particular interest for the project where principles and methods for capturing and representation of design rationale by utilization of 3D MBD (Model Based Definition) have been investigated.

5. Objective

The project's overall objective was to improve:

- strategies for part and process measurement and control to achieve reduced variation and improved ability to manufacture parts with future tighter tolerances.
- interpretation of requirements specification and verification to reduce ambiguities and enable equal part quality measures between production sites.
- design of in-process part requirements to enable faster process design optimization and production in smaller batches with increased number of prototypes.
- standardization and dissemination of common work methods to eliminate duplication of method development and establishment of best practice for process design

By that the project aimed to contribute to:

- Shorter product introductions through methods and tools for, a better first definition of production requirements, and improved manufacturability by early involvement of manufacturing aspects in product design.
- Improved quality control through ability to relate production and process requirements to product and process functions.

- Finer and continuous control of part quality by optimized use of production resources, knowledge about where to measure less and where to measure more.
- Supplementary process evaluation methods in addition to capability indexes as acceptance criteria's

6. Results and deliverables

To achieve stated objectives the project was organized in four Work Packages (WP) as described in the following table.

Work Package 1	Project management
Leader	Magnus Lundgren, KTH
Description of contents	Plan, control and communicate project progress.
Method	Continuous progress and result documentation. Annual general assemblies.
Deliverables	Regular progress reporting (KTH) Project meetings (KTH) General assembly (KTH)
Work Package 2	Quality engineering method development
Leader	Theodoros Laspas, KTH
Description of contents	Development of theory, methods and standard utilization for quality engineering.
Method	Identify industrial needs. Develop methods and prototype tools for process design.
Deliverables	In-process part tolerance analysis method. Measurement method uncertainty assessment. Measurement frequency and sampling density guide. Capability assessment. Classification of requirement.
Work Package 3	Model based process design
Leader	Magnus Lundgren, KTH
Description of contents	Implement developed tools and methods.

	Study and refine solutions.
Method	Validation of technology. Development of public demonstrators representing products and processes in modern production.
Deliverables	3D tolerance and variation modelling. MBD application utilising ISO GPS in process design. Process design rational, relating specification and function.
Work Package 4	Project result dissemination
Leader	Helena Björk, RISE
Description of contents	Dissemination and application of project results in industry and academy.
Method	Dissemination of results through publicly available sources. Use project results to develop engineering education. Present result at national and international industry seminars.
Deliverables	Handbook for industry practice. Course modules for engineering education. Scientific publications. Industry seminars.

6.1 WP2 Quality engineering method development

The focus for Work Package 2 was development of methods for in-process part tolerance analysis, measurement method uncertainty assessment, measurement frequency determination, capability assessment based on type of ISO GPS specification, and finalization of the ISO 24096 standard for classification of requirements.

6.1.1 In-process part tolerance analysis method.

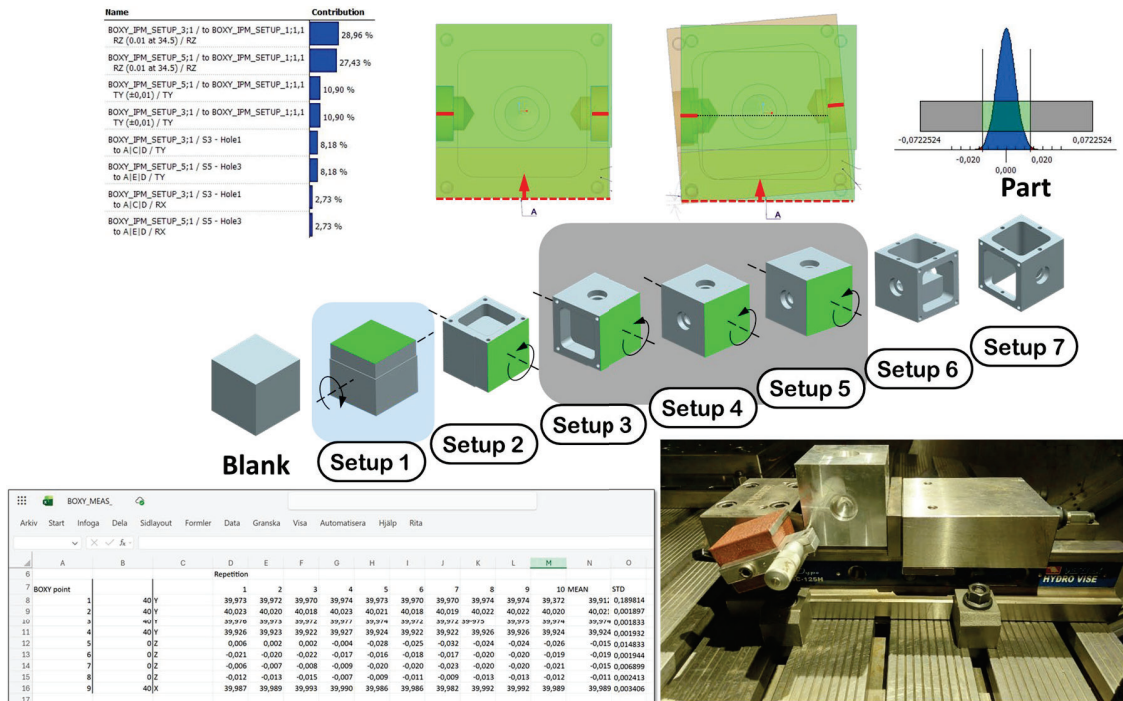


Figure 1- In-process part tolerance analysis

Process design includes definition of dimensional and geometrical product specifications and verification. Workpiece shape variation is caused by systematic and random deviations. Examples of variation sources in machining are machine tool kinematics and fixture clamping. Propagation of shape variations in multi-step manufacturing processes, constrained by tolerance chains, is the consequence of sequenced operations defined in process planning. A key task in process planning is to define in-process workpiece (IPW) tolerances for efficient production ensuring conformance to the product design specification and good utilization of the manufacturing resources.

A study was conducted within the project with the purpose of investigating the variation occurring due to clamping practices and how this stacks up in the final manufactured part. The study was first conducted theoretically where the software Sigmetrix CETOL 6σ was used to model tolerance stack up for a test component machined in a multi-step process. Sigmetrix CETOL 6σ, provided by the project partner Ariadne AB is a 3D model-based tolerance analysis software which normally is used to predict and visualize how assembly variation impacts product performance, but in this project the software was used in an innovative way to analyze and present the effects of clamping location errors.

As a second part of the study physical experiments were performed at a HERMLE C50U machining center. Three “critical” setups were defined and “perfect” parts representing the in-process workpiece at each setup were machined. For each setup the corresponding “perfect” part was clamped with adequate force in a vise where the “nominal” workpiece

position was measured and stored as reference. Then different operators were executing the following steps for each setup:

- The operator was instructed to place the workpiece in the vise and align and place the workpiece as good as possible to the fixed jaw of the vise and a side stop of the vise.
- With the workpiece at intended position the operator clamped the part using the manifold of the vise. As one purpose of the study was to investigate the effect caused by clamping force variation the operator was instructed to rely on their own estimate on sufficient clamping force.
- When the part was clamped a measurement program was run in the machine which measured and stored the real position for a set of pre-defined points.
- For each setup the workpiece was clamped/unclamped 10 times.
- The measurement result for each setup (and operator) was transferred to a spreadsheet where the mean and standard deviation for each measurement point and repetition were calculated.

6.1.2 Measurement method uncertainty assessment



Figure 2- Test specimen for measure method uncertainty evaluation

The project developed and evaluated methods for measurement method uncertainty based in the ISO GPS framework. The applied scope selected was size (length and diameter) measurements. Test specimens were manufactured (some of these illustrated in figure below) with controlled form deviations that are large in relation to the size to be evaluated. The form deviations were designed to give commonly used measurement methods high impact on the measurement results.

Quantification of measurement method uncertainty can be done by counting deviations between specification operators and chosen verification operators (concepts defined in the ISO GPS standard). However, in industry it is often of more interest to study its effect on measurement result. In the case of size measurement is the effect highly dependent on the form deviation from the ideal (even if there are no form requirements).

The illustrated test specimen was designed and manufactured with 2 main type of form deviations both with 3 and 5 deviation “loops” and each of these in 3 different deviation magnitudes, in total 12 specimens. The types of form deviation can shortly be described as “constant width” (indicated with the prefix CS) and “constant cross-section size” (indicated with the prefix LP). The deviation type “constant width” gives zero contribution to the variation in measurement result from a measurement method equal to using a calliper. The deviation type “constant cross-section size” gives zero contributions to the variation in measurement result from a measurement method equal to the ISO GPS definition of size.

By using different measurement methods and compare the results (sometimes known as counter-measurement) together with information on form deviations and uncertainty contribution from the measurement implementation (device imperfection etc.) can the effect of measurement method uncertainty be assessed. Note that the result will only be valid under the form condition in the study.

This project result can be seen as a formalised, structured and ISO GPS aligned version of assessment methods practiced in industry for decades. With manufacturing process knowledge regarding capability, predictability and form deviations can measurement method uncertainty be managed and enable simplified measurement procedures, conversion of in-process tolerance types and give efficient process control.

6.1.3 Classification of requirement.



Figure 3- ISO 24096 Technical product documentation [TPD] - Classification of requirements

This work, initiated in earlier FFI-project MPQP - Model driven process and quality planning (2014-01413) is an important project result. The result published as the international standard ISO 24096 (2024) provides a framework for building systems to enable the classification of requirements. The standard has been developed mainly to be implemented within industry, e.g. the automotive and aerospace industries, but can also be used in other engineering fields. Requirement classification is a way to communicate the level of consequences of nonconformity of requirements for subsequent parties and stakeholders.

The standard which consists of two parts (ISO 24096-1 and ISO 24096-2) addresses the classification of requirements and provides a framework for building systems to enable the classification of requirements. This facilitates the guiding of production and quality assurance resources (e.g. purchasing, production planning, control, revision).

6.2 WP3 Model based process design

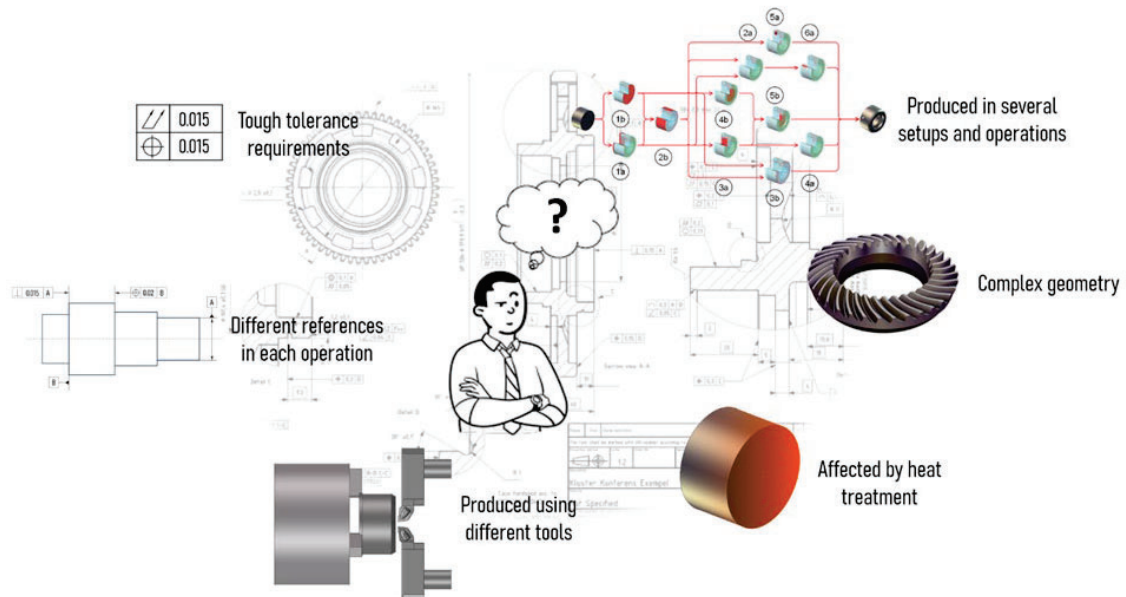


Figure 4- Structural process planning

An important part of the project has been to emphasize that the process planning activity, from a principal point of view, has more in common with the design activity than what differentiates them. The concept of function is of equal importance in process planning as in design as process planning can be regarded as an activity in which a set of functions required to transform a blank into a product in an anticipated operating environment are developed and communicated. In a well-designed process every single operation has a purpose in the sense of performing an intended function. Hence process design representation and communication of process design intent have been a focus area of the project.

$$C_I = \overset{\text{affected by design}}{K_a \times K_b \times K_c \times K_d} \times \overset{\text{affected by process planning}}{K_e \times K_f \times \prod_{i=1}^n K_{g_i} \times K_h}$$

Figure 5- Criticality Index

Here, the project partner Scania has developed a methodology to characterize components from a process planning perspective via a criticality index. This index, C_I , is constituted of factors affected by design: tolerance size / surface roughness (K_a), type of tolerance (K_b), feature size (K_c) and feature type (K_d), and factors affected by process planning: production complexity (K_e), heat treatment effect (K_f), machine performance of the i^{th} process (K_{g_i}), and tool effect (K_h).

6.2.1 Factors affected by design

The K_a factor increases with tighter tolerances as they result in increased setup and inspection time, higher tooling and equipment costs, need for more frequent inspections, greater complexity of machining operations and difficulty in maintaining tolerances over time.

The K_b factor is affected by type of workpiece material, part geometry, feature orientation and type of tolerance, i.e. dimensional tolerances and geometrical tolerances where linear dimensional tolerances are less difficult to achieve than angular dimensional tolerances, and geometrical tolerances as straightness are less difficult than run-out.

The K_c factor increases as well for larger features as for small features, where requirement of high-precision machining tools and techniques, likelihood for tool breakage and possible chip evacuation challenges as well as measurement difficulties contribute to increase the K_c factor for small features. On the other hand, challenges that contribute to increasing the K_c factor for large features are for instance that they require larger and more powerful machining equipment, material removal rates can be slower and heat generation can affect accuracy and quality.

The K_d factor, feature type, is related to geometric complexity where for instance complex features require more intricate (complex) tool paths which increases the time required for machining and may impact production efficiency. Machining accuracy is also challenging for complex features which may require advanced techniques and specialized cutting tools. Furthermore, measuring complex features is challenging due to intricate geometry, requiring specialized tools and techniques. All together this contributes to increasing the K_d factor.

6.2.2 Factors affected by process planning

Production complexity, K_e , is related to setup and machining strategies, where related features that can be machined in the same setup with the same tool are less complex than related features that must be machined in different setups with different tools. Hence the latter will contribute to increased production complexity which is reflected in a higher K_e value. Production complexity can be illustrated as in the picture below with a part which has two grooves (detail A & B) that are related to datum C and D with the same location tolerance. Datum C is related to datum A & B, and datum D is related to datum C, thus creating a reference dependency graph as presented in the picture.

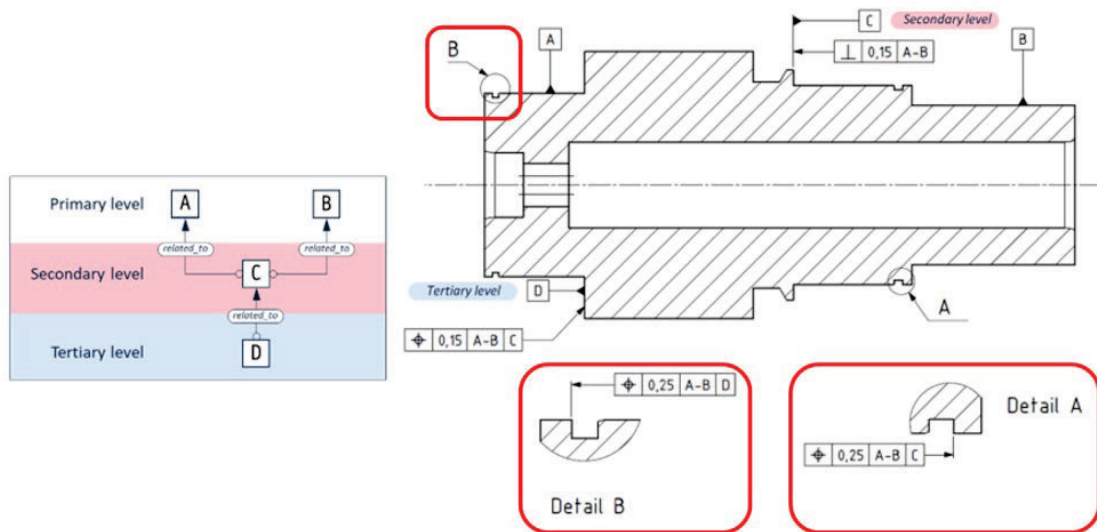


Figure 6 - Example on production complexity (Scania AB)

Heat treatment effect, K_f , is a binary factor in the sense that a feature is considered not to be affected by heat treatment if there is no heat treatment on the surfaces of the feature/references or if all surfaces of the feature/references will be machined after the heat treatment.

The machine performance factor, K_g , is related to accuracy, surface finish, dimensional stability and production speed, were processes capable of achieve narrow tolerances and smooth surface finish at the cost of decreased production speed, e.g. broaching, grinding and honing will increase the K_g factor.

The tool effect factor, K_h , depends on the number of tools used to produce the feature. The more tools required the higher K_h factor.

7. Dissemination and publications

The most important arena for result dissemination has been within production engineering education where for instance the results from WP2 about measurement method uncertainty assessment is used in the course MG2010 Modern Industrial Metrology at KTH. The theoretical foundation of process design rationale and process design intent are fundamental in the two courses MG2130 Modelling and Simulation of Industrial Processes and MG2036 Computer Aided Manufacturing – CAM. Project results have also been disseminated at internal workshops within the project, at the annual Swedish Component Cluster Conference, as well as in the context of international standardization. Scientific work in the project has also contributed to the doctoral thesis *Performance evaluation of machine tools – A methodology for loaded testing of machine tools* by Theodoros Laspas.

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

8. Conclusions and future research

Due to challenges in terms of loss of key personal resources and failure in critical equipment some objectives (deliverables) were not fulfilled. However, the project has despite that managed to deliver valuable results in line with its stated objectives. Since the project start in 2022 substantial progress has been made within the development of artificial intelligence (AI). The project consortium strongly believes that project results can be utilised for further development of Computer Aided Engineering software for collaborative process and quality planning that use AI to support skilled engineers, shorten development time and improve quality.

9. Participating parties and contact persons

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