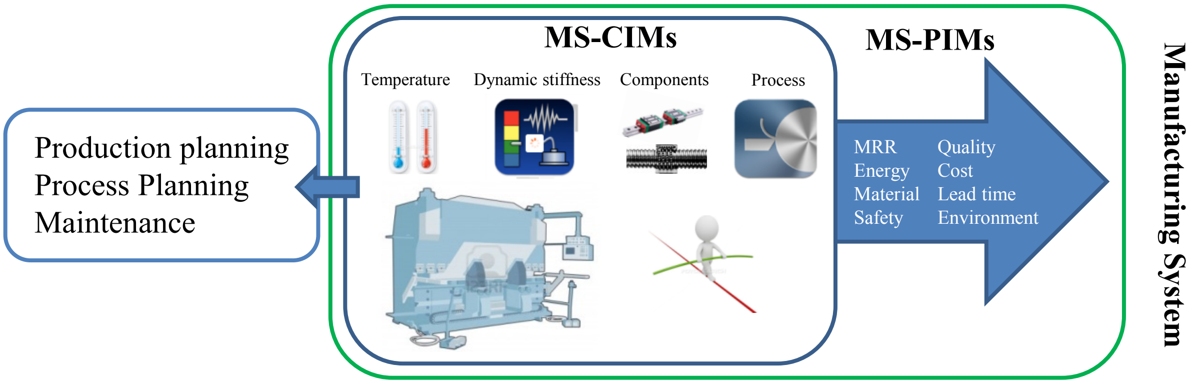
COMPIT
Capability of Machining Systems and Performance Improvement Technologies



Relationship between machining systems (MS) Capability Indicator Metrics (CIMs) and MS Performance Indicator Metrics (PIMs)

Project within Hållbar produktion

Authors	Andreas Archenti (project manager)	KTH Royal Institute of Technology
	Mahdi Eynian	University West
	Tomas Österlind, Theodoros Laspas	KTH Royal Institute of Technology

Date 2016-12-08

Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

Background

A machining system (MS) is one of the most important manufacturing units in any production system and therefore its capability has an important bearing on e.g. the flexibility, accuracy and eco-performance of the system. The capability of a MS describes the ability of the system to produce parts within the dimensional tolerances and surface quality specified by component design. Factors affecting the capability are determined by the machine tool, machining process and their mutual interactions.

The existing methodologies used today are decoupled from the operational environment and therefore fail in many situations to identify the underlying problems for finding robust solutions.

Project definition and Objectives

A MS capability profile is defined by factors that are affecting the MS's accuracy and precision: (i) kinematics and positioning; (ii) static stiffness; (iii) thermal behaviour; (iv) dynamic stability. If quantified, these factors form the MS Capability Indicator Metrics, MS-CIM. MS performance is characterized by factors that are quantified as MS Performance Indicator Metrics, MS-PIM, such as: (i) MRR (Material Removal Rate); (ii) power consumption; (iii) cost; (iv) safety (this refers to a controllable, stable process); (v) environmental impact; (vi) quality (this refers to accuracy and precision).

The objective of the project was to develop a platform with four main tasks:

- Formulation of a model to link the MS-CIM domain to MS-PIM domain.
- MS capability profile evaluation methodology and characterization of MS-CIMs.
- Industrial case studies to validate and demonstrate the proposed concept.
- Analyse the effect of MS-CIM on MS-PIM.

Project constellation and organisation of work

The project consortium comprised partners with long experience in manufacturing processes including two research and four industrial partners namely KTH Royal Institute of Technology, University West, Scania CV AB, AB Volvo, Leax Mekaniska AB Falun, GKN Aerospace Sweden AB and SAAB Aeronautics. While the research partners, KTH and University West, was responsible for the development work, the industrial partners played a vital role in supporting the research work through appropriate case studies.

The project was managed according to the FFI-project format with an overall steering group with the partners and a consortium agreement. The project activities were distributed in six work packages. WP1 was dealing with project coordination and management. In WP2 the framework and the main concept on MS capability was formulated. The concepts of MS-CIMs and MS-PIMs are introduced. State-of-the-art developed technologies (WP3) was adapted to the level of industrial implementation, standardization and training (WP4). Work package 5 focused on the exploiting of existing knowledge by combining research findings from FFI projects ‘Robust machining and ‘Feature Based Operation Planning’. In work package 6 project findings are disseminate trough seminars, workshops and training courses.

Main technical and scientific results
The COMPIT project resulted in further development of test instruments and methodologies, validated through industrial case studies, which will be available for implementation in industry. By using these tools companies can define and select CIMs that best relates to the requirement specification of their products (e.g. quasi-static stiffness). Further, by using the CIM-PIM relational model, users can understand how the variations in the parameters describing the machining system are related to the variations of system performance.

The use of the CIM-PIM concept will enhance the understanding of industrial practioners and researchers about interactions between the machining system capability and performance and help them in developing better performance improvement solutions at a faster pace. Developments have been published in 32 scientific publications.

2. Sammanfattning på Svenska

Bakgrund
Bearbetningssystem (machining systems - MS) är en av de viktigaste enheterna i produktionssystem och deras duglighet (capability) har stor inverkan på systemens flexibilitet, noggrannhet och miljöpåverkan. Dugligheten beskriver systemens förmågan att producera komponenter inom toleranser som anges av komponentdesign. Dugligheten bestäms av maskinen och bearbetningsprocess egenskaper och deras inbördes växelverkan. Befintliga testmetoder för duglighet relaterar inte testutfallet till grundorsaken för en avvikelse och kan därför i många fall inte identifiera de underliggande orsakerna till avvikelser.

Projektmål och syfte
Ett bearbetningssystems duglighetsprofil påverkar systemets felxibilitet, noggrannhet och precision kan delas in i följande områden: (i) kinematik och positionering; (ii) statisk; (iii) termisk; (iv) dynamisk egenskaper. Dessa faktorer kan kvantifieras som bearbetningssystem duglighetsparametrar (Machining System Capability Indicator Metrics - MS-CIMs). Bearbetningssystems prestanda kan mätas och kvantifieras genom s.k. prestandaindikatorer (Machining System Performance Indicator Metrics (MS-PIMs) så som: material avverkning; (ii) effektförbrukning; (iii) kostnad; (iv) säkerhet (detta refererar till en robust och stabil process); (v) miljöpåverkan; (vi) kvalitet (detta avser noggrannhet och precision).

Syftet med FFI COMPIT-projektet var att utveckla en plattform som kopplar samman bearbetningssystems duglighet (MS-CIM) och prestanda (MS-PIM) genom att:

- utveckla en modell som länkar MS-CIM domän till MS-PIM-domänen.
- utveckla och anpassa utvärderingsmetod för duglighet (MS-CIM).
- testa, utvärdera konceptet och teknologierna i industriella fallstudier
- analysera effekten av MS-CIM på MS-PIM och genom detta bygga ny kunskap som kan användas inom akademin och industrin.

Projekt konstellation och organisation
Projektkonsortiet bestod av partners med lång erfarenhet av tillverkning av komponenter och inkluderande två forsknings och fyra industripartners: Kungliga Tekniska högskolan,

Högskolan Väst, Scania CV AB, AB Volvo, Leax AB, GKN Aerospace Sweden AB samt Saab Aeronautics.
KTH och Högskolan Väst var ansvarig för utvecklingsarbetet, och industripartnerna var ansvariga för att tillhanda hålla lämpliga fallstudier.

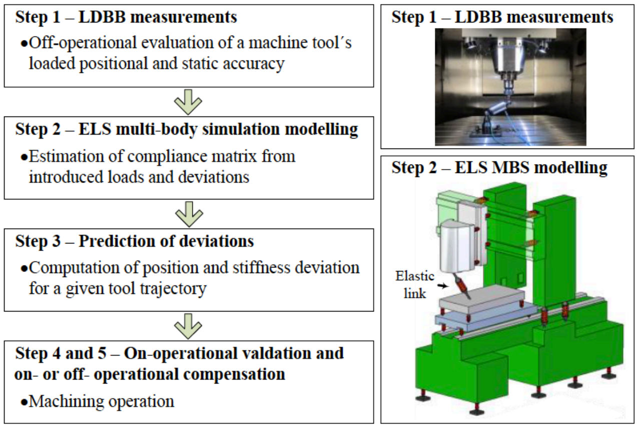
Projektet organiserades enligt Vinnovas FFIs format med en styrgrupp och projektavtal. Arbete fördelas i sex arbetspaket där arbetspaket 1 ansvarade för projektledning och övergripande ekonomi. Projektets övergripande koncept utvecklades i arbetspaket 2, begreppen MS-CIM och MS-PIM introducerades. Mätinstrument och mätmetodik (arbetspaket 3) anpassades till för industriell tillämpning, standardisering och utbildning (arbetspaket 4). Arbetspaket fem fokuserade på exploatering av befintlig kunskap genom att kombinera forskningsresultat från FFI projekten Robust bearbetning och Feature Baserat operationsplanering. I arbetspaketet 6 spreds resultaten via bla. utbildning och träning.

Viktigaste tekniska och vetenskapliga resultat

De viktigaste tekniska och vetenskapliga resultaten från projektet var:

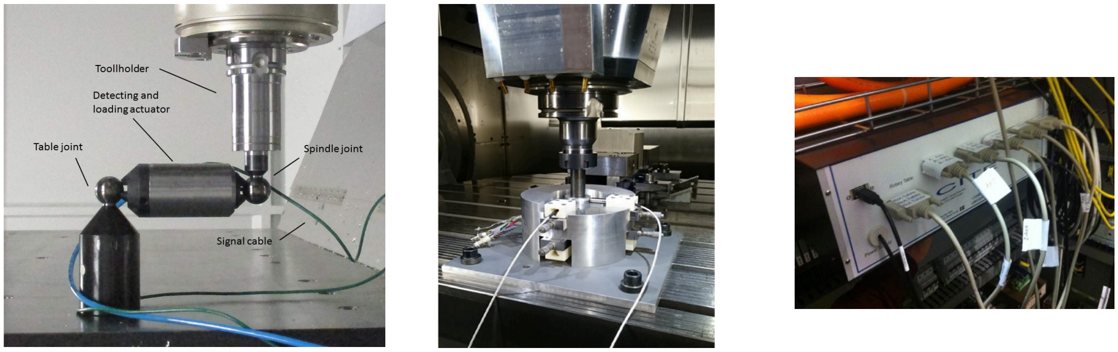
1. framtagning av en helt unik metodik kallad *Elastically Linked Systems* som sammankopplar maskiners kapabilitet med tex produkt kvalitet (MS CIM-MS PIM), se Figur 1.
2. vidareutveckling av mätinstrumenten *Loaded Double ball bar (LDBB*, *Contactless excitation and response systems* (CERS) och CNC Integrity Tracing System (*CITE)*.
3. ny kunskap om hur bearbetningssystems beter sig under belastat s.k. operationellt tillstånd.

Forskningsarbetet har publicerats i en vetenskaplig licentiatavhandling samt 32 vetenskapliga publikationer inkluderande 10 tekniska rapporter, se publikationslistan i slutet av rapporten.



Figur 01. Konceptet ELS - Elastically Linked Systems introducerades i projektet.

*ELS-m*etodiken innefattar (se Figur 1) fyra steg där det första steget är inhämtning av data från verkliga belastad bearbetning system (steg 1). Olika mätinstrument användas för insamling av information om systemens egenskaper. I FFI COMPIT projektet användes och vidareutvecklades mätinstrumenten belastad ballbar (LDBB) och kontaktlös excitering och responsmätning (CERS), och datainsamlingssystemet CITE, se Figur 02a-c.



(a) (b) (c)

Figur 02. a) Belastad ballbar, b) CERS, och c) CITE.

I Steg 2 används en analytisk modell som sammankopplade bearbetningssystemets kinematiks och kvasi-statiska beteende. Modellen kalibreras av mätdata från verkliga maskiners (från steg 1). I steg 3 och steg 4 används modellen för att numeriskt beräkna deformationer och avvikelse i systemet under belastat tillstånd.

Fallstudier

Genom att använda den utvecklade ELS och CIM-PIM plattformen samt de industrianpassade mätinstrumenten i fallstudier kan företag identifiera och välja de indikatorer som bäst avspeglar kravspecifikation för produkter (t ex kvasi-statiska styvhet inverkan på komponenters geometri).

Ny kunskap

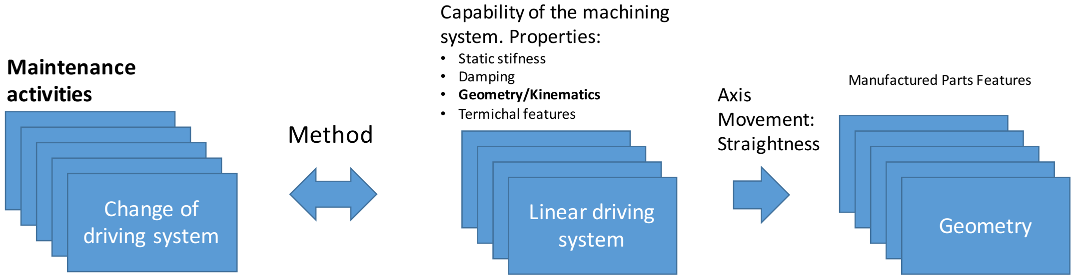
Genom att använda ELS metodiken och CIM-PIM samt de industrianpassade mätinstrumenten kan företag identifiera och välja de indikatorer som bäst avspeglar kravspecifikation för sina produkter (t ex kvasi-statiska styvhet inverkan på komponenters geometri). Användningen av CIM-PIM konceptet kommer att öka förståelsen hos industrin om vilka faktorer som påverkar t ex deformationer och avvikelse. Forskare kan också utveckla ny kunskap som kan användas för att bättre prediktera systemens beteende och leda till kunskaps-baserad utveckling. Man kan redan nu se att deltagande företag har börjat implementera flera tekniker som användes vid beredning och anskaffning av nya maskinsystem.

Forskare kan också utveckla ny kunskap som kan användas för att bättre prediktera systemens beteende och leda till kunskaps-baserad utveckling.

Projektet vidareutvecklade också befintliga innovativt mätinstrument (LDBB, CERS och CITE) samt koncept för utnyttjande av maskiners inbyggda givare som möjliggör identifiering av verktygsmaskiners duglighet under operationslika förhållanden. Detta innebär att företag och forskare har helt nya möjligheter att skapa kunskap genom noggranna analyser av maskiners och processers fysikaliska egenskaper. Kunskap som kan användas för produktion där noggrannheten eller flexibiliteten kan ökas men även för underhåll för att identifiera källor till variationer.

Resultat från COMPIT leder till:

- ökad industriell förståelse om vilka faktorer som påverkar t ex deformationer och avvikelser vid tillverkning av avancerade komponenter. Detta leder bl.a. till optimerade beredningar som i sin tur resulterar i högre utnyttjandegrad och lägre energiförbrukning.
- ökad industriell förståelse för vilka källor till avvikelse i maskinbearbetningssystem som leder till minskad kvalitet eller flexibilitet.
- koppling mellan underhåll och produktion kan göras. Källor till variationer uppkommer ofta inom underhålls domän, tex förslitning av en linjäraxel. Genom ELS kan man koppla effekten av den variationen på utfallet på variation på produkt (se Figur 03).



Figur 03. ELS konceptet kan användas för att länka underhålls domänen med komponenttillverknings domänen.

Vidare användning

Vidare kan kunskaperna som genererats genom FFI COMPIT användas som ett verktyg vid digitalisering av svensk industri. Den utvecklad generiska metodiken kan användas som grund för identifiering av vilka parametrar som skall mätas med givare och för att svar på frågorna, 'vad som skall mätas', 'hur ska det mätas', och 'när ska det mätas'.

3. Background

A machining system (MS) is one of the most important manufacturing units in any production system and therefore its capability has an important bearing on the e.g. flexibility, accuracy and eco-performance of the system. The capability of a MS describes the ability of the system to produce parts within the dimensional tolerances and surface quality specified by component design. Factors affecting the capability are determined by the machine tool, machining process and their mutual interactions.

The existing capability assessment methodologies are decoupled from the operational environment and therefore fail to identify the underlying problems for finding robust solutions. The divide between the capability analysis and the performance analysis is a major cause of misleading industry in understanding the capacity of both their existing production lines.

4. Objective

A MS capability profile is defined by factors that are affecting the MS's accuracy and precision: (i) kinematics and positioning; (ii) static stiffness; (iii) thermal behaviour; (iv) dynamic stability. If quantified, these factors form the MS Capability Indicator Metrics, MS-CIM, see Figure 1. MS performance is characterized by factors that are quantified as MS Performance Indicator Metrics, MS-PIM, such as: (i) MRR (Material Removal Rate); (ii) power consumption; (iii) cost; (iv) safety (this refers to a controllable, stable process); (v) environmental impact; (vi) quality (this refers to accuracy and precision), see Figure 1.

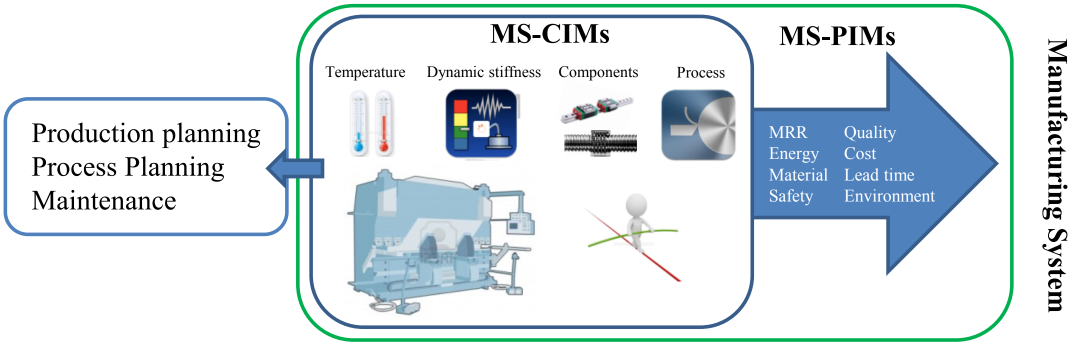


Figure 1. Relationship between MS-CIMs and MS-PIMs.

The objective was to develop a platform with four main ingredients:

- Formulation of a model to link the MS-CIM to MS-PIM (WP 2 and WP 5).
- MS capability profile evaluation methodology of MS-CIMs (WP 3).
- Industrial case studies to demonstrate the proposed concept (WP 4 and WP 6).
- Analyse the effect of MS-CIM on MS-PIM (WP 5).

Though the capability concept of MS-CIMs and their relationship to MS-PIMs is generic the main objective of the FFI COMPIT project has been at the development of methodologies and tools for evaluation of machine tools' capability.

5. Project realization

The project was managed according to the FFI-project format with an overall steering group with the partners and a consortium agreement. The project activities were distributed in six work packages. WP1 was dealing with project coordination and management. In WP2 the framework and the main concept on MS capability was formulated. The concepts of MS-CIMs and MS-PIMs are introduced. State-of-the-art developed technologies (WP3) was adapted to the level of industrial demonstration, standardization and training (WP4). Work package 5 focused on the exploiting of existing knowledge by combining research findings from FFI projects 'Robust machining and 'Feature Based Operation Planning'.
In work package 6 project findings are disseminate trough seminars, workshops and training course.

The project consortium comprised partners with long experience in manufacturing processes including two research and four industrial partners namely KTH Royal Institute of Technology, University West, Scania CV AB, AB Volvo, Leax Mekaniska AB Falun, GKN Aerospace Sweden AB and SAAB Aeronautics. While the research partners, KTH and University West, was responsible for the development work, the industrial partners played a vital role in supporting the research work through appropriate case studies.

The project started January 2013 and completed 31 October 2016. The total financial framework was 15.2 MSEK, whereof 7.6 MSEK has been supported by VINNOVA within the FFI-subprogramme Sustainable Production grant no. 2012-03684.

6. Results and deliverables

The tangible results are listed as results in each activity below.

Capability and performance framework (WP 2)

The COMPIT projects used the Elastically Linked System (ELS) concepts (and the top-down and bottom-up modelling approach described in WP 5) to associate and demonstrate the link between the MS-CIMs to MS-PIMs. In case of ELS a top-down approach is used to identify the stiffness matrix of the machine tool under loaded conditions by performing a set of measurements in the machine tool workspace, Figure 2. (Archenti, 2014)

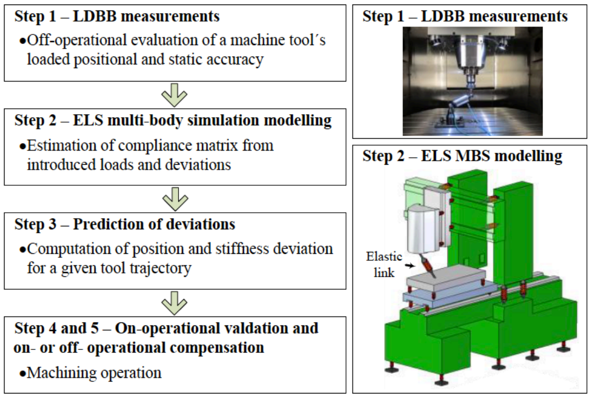


Figure 2. Computational steps for linking machining system capability to part accuracy. (Archenti, 2014)

Through this, the volumetric deviation can be computed in an ELS multi-body simulation model and the stiffness matrix of the kinematic chain is evaluated.

Deliverables from WP 2: a framework connecting MS-CIMs and MS-PIMs.

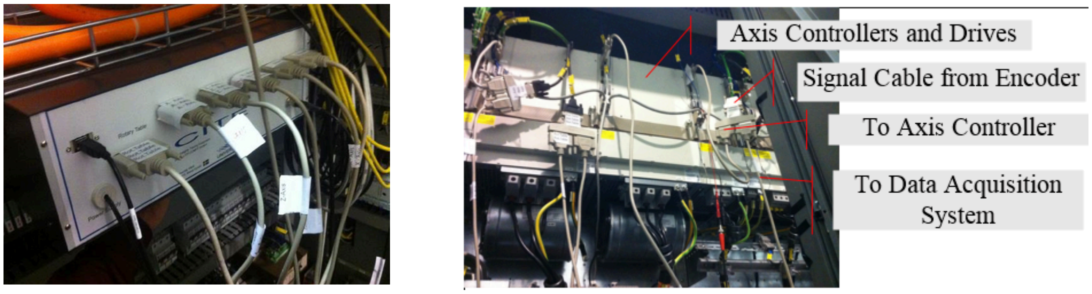
Evaluation tools and methodologies used in COMPIT (WP 3)

In this task the methods were introduced to evaluate the MS-CIMs defined by the project. By closing the loop between the tool and workpiece, the interaction machine-process will be simulated and by this, MS-CIMs representing the static and dynamic conditions can be evaluated. A modified LDBB with improved functions to simulate the process stiffness were used to evaluate the MS static behaviour in the working space, see Figure 3a (Laspas and Archenti, 2016). By this the optimal location of the workpiece and the orientation of cutting force can be selected. Evaluation of dynamic behaviour using the improved CERS, see Figure 3b. The contactless technique gives the possibility to evaluate the dynamic characteristics of the rotating parts, such as spindles; in this way, the correlation between rotational speed and dynamic characteristics can be identified (Montalban and Grigoriadis, 2016).

(a) (b)

Figure 3. a) Loaded double ball bar – LDBB, and b) Contactless excitation and response system – CERS.

Multiple versions of CNC Integrity Tracing System (CITE) system hardware and software were developed to gather signals from encoders reliably. These systems enabled simultaneous measurement of the movements of the machine tool's linear and rotary axis and its spindle. Furthermore, a Matlab® based graphical user interface and data acquisition system was developed to enable easy-to-learn application of the system. The system was found useful in explaining the surface waviness problem of curved machined sections. Furthermore, a monitoring system based on encoder signals was developed, and its sensitivity and repeatability was compared to well-established force sensors across different machine tools on different machine axis (Enyan and Wretland, 2016). The CITE system for the five axis machine tool was furthermore used for fine tuning of the setting parameters for tool path generation software and machine tool control system in five axis machining of curved surface of jet engine blades. The objective of the implementation and further developments of the CITE was: (a) process monitoring for detection of tool wear, (b) process monitoring for coupling machining state to generated surface roughness and (c) application of the method for fault diagnosis to detect missing or broken cutting edge.



(a) (b)

Figure 4. CITE connected to the control and servo drive system of the machine tool.

Deliverables from WP 3: instruments and methods for evaluation of CIMs representing static and dynamic behaviours and measuring techniques using internal and external sensors.

Implementation through industrial case studies (WP 4)

The purpose of the case studies was the evaluation of MS-CIM, representing quasi-static and kinematic accuracy of three different machine tools for cylinder block manufacturing and one machine tool for aluminum parts for aeronautical applications, using the LDBB. In the first case study the LDBB measurement results were compared with results obtained by the BAS machining test. The BAS test is a machining test method that by processing and measuring test samples determines the machine tool's performance and stability (BAS

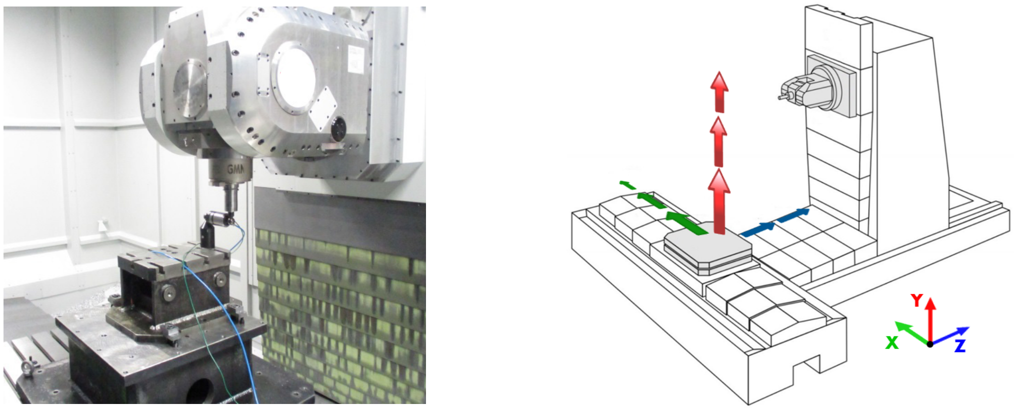
Maskintester, 1971). In this case study, a special adaptor plate has been made that allowed mounting of the LDBB table joint and BAS test piece on the side of an engine block, see Figure 5a-b.

(a) (b)

Figure 5 a) Illustration of setup of LDBB on the adaptor plate on the side of an engine block in a machining centre, and b) the machined test piece mounted on the engine block.

Mounting the table joint on the engine block allows the measurement of the induced deformations exactly at the areas of interest, including any errors that might be caused due to fixturing. In this sense, the measurement results offer a more holistic approach that better captures the capability of the system as a whole. Additionally, it demonstrates the flexibility and adaptability of the LDBB system in different conditions and requirements. In a good agreement with the BAS machining test for all machines, the results produced by the LDBB test proved that it can be a reliable method for evaluating quasi-static behavior and accuracy of machine tools. It is a fast method that can act as a replacement of machining tests (Laspas et. al, 2015). Furthermore, it is important to observe the instruments ability to detect motion dynamic, play and servo errors of the machine tool, in combination with the capability to apply force to the structure.

In the second case study a 6 axis machining center was investigated. The machine was equipped with a rotary tilting head (A and C axis) and a rotary table (B axis) with a pallet system that offers flexibility and high productivity in machining of complex features and surfaces in single setup, see Figure 6a. In order to get a good comparison between the machine tool three planes - XY, YZ and ZX - in the workspace and to utilize most of the machine axis (linear and rotary), six different measurement positions were specified (Laspas and Archenti, 2016).



(a) (b)

Figure 6 a) Measurement setup for Pos3, and b) representation of the stiffness within the workspace. Size and number of the arrows represent the magnitude of stiffness in the respective axis directions, and b, a general trend is visible in which Y direction is the stiffest in the respective planes and Z the less stiff of the three directions.

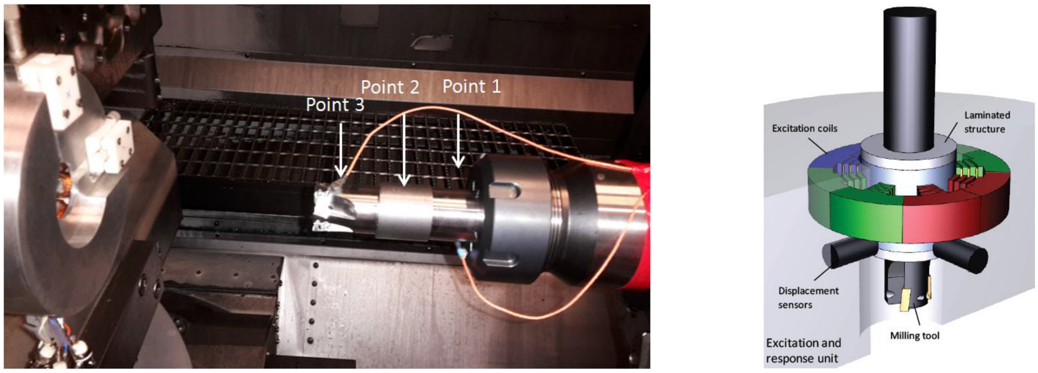
The cumulative calculated stiffness is illustrated in Figure 6b and the stiffness results in Table 1. As it was expected from the individual positions results, Y direction and hence possibly the Y axis of the machine, has the highest stiffness in all planes. In addition, it is observed that the Y positions have an effect to the stiffness of all axis and directions. Plane ZX, as it includes the two less stiff directions (which can be related to the respective axis), has the lower maximum stiffness especially when measuring in a Y position higher from the table surface. The reason of the Y axis effect can be partially explained by the higher moment generated due to the higher position of Y axis and the narrow width of the column (Z axis) of the machine tool. Results from this case study on MS-CIM show both in terms of kinematic and static accuracy that the geometry of the machine tool and more specifically the height of the column can have a significant effect on the accuracy of the systems (Laspas and Archenti, 2016). In machining terms, the column tilting in the presence of machining forces could result in inaccuracies in the form and dimension of the machined part. The LDBB measurement instrument allowed measuring these effects under controllable load at different planes.

Table 1. Cumulative results for stiffness of the different planes in the six positions. (technical report)

	CCW	**CW**	**CCW**	**CW**
Plane ZX	**Pos1**		**Pos2**	
Max (N/µm)	17.9	18	16	15.9
direction	X	X	X	X
Min (N/µm)	12.8	12.9	10.5	10.4
direction	Z	Z	Z	Z
Plane XY	**Pos3**		**Pos6**	
Max (N/µm)	18.9	18.6	18.2	18.4
direction	Y	Y	Y	Y
Min (N/µm)	16.4	15.9	13.1	13
Direction	X	X	X	X
Plane YZ	**Pos5** corrected		**Pos7**	
Max (N/µm)	21.6	21.2	19.4	19.1
direction	Y	Y	Y	Y
Min (N/µm)	12.7	13.0	10.8	10.8
direction	Z	Z	Z	Z

MS-CIM represented as dynamic condition

Forming the interface between the machine tool structure and the cutting tool, the dynamic characteristics of the spindle plays a critical role in machining centers. Accuracy, speed range capability, high rigidity, high damping capacity, and stable operating temperature are a few of the requirements of the spindle unit. The purpose of the case study was to identify and evaluate MS-CIM under gyroscopic effect, that is under different rotational speeds, using the CERS, see Figure 7a-b. With this method the MS-CIM can be obtained in terms of dynamic accuracy of the spindle unit and the results can be compared with conventional experimental modal analysis (EMA). (Montalban, 2016)



(a) (b)

Figure 7 a) Test set-up in one of the investigate machine tools, and b) the contactless excitation system.

The EMA and CERS results revealed that there was not a significant effect of the rotational speed on the dynamic properties of the spindle at the tested speed range. (Montalban, 2016)

MS-CIM represented as dynamic condition captured by machine tools encoders

Tool wear detection sensitivity (a) was demonstrated and its repeatability and sensitivity was compared across two machine tools, with six drilling tools of various wear levels against commonly used cutting force dynamometers (Enyan and Wretland, 2016); furthermore, a frequency domain approach was investigated for drilling wear detection from internal signals in (Hansson, 2016). The relationship between surface roughness/waviness and axis movement imperfections (b) was demonstrated in a thesis work in milling of a curved path with an endmill (Liu, 2015). In detection of missing or broken cutting edges, in a separate work, in milling, various signal features were examined for detection of insert wear in a multi-tooth milling cutter (Beno et. al., 2013). The activities were facilitated by development of the CITE system to be capable of simultaneous data acquisition from all axis of a five axis machine tool, in addition to development of CITE system with capability to work with the available 3 axis machine tool. In retrospect, it would have been great if a separate task was devoted for further development of CITE hardware. This enabled COMPIT partners to use the CITE system in an innovative manner for applications not designed in the original project proposal, e.g. for fine tuning of parameters of both the five-axis machine tools also the computer aided manufacturing systems used for tool path generation in performing of complex five axis movements needed in manufacturing of contoured surfaces.

Deliverables from WP 4: The different industrial case studies aimed to obtain the MS-CIM through characterization with LDBB, CERS and CITE and to demonstrated the importance of correct measurements and evaluation process. The different tasks extensively used

CERS and LDBB measurements together with conventional modal analysis, cutting force measurements and surface characterization to couple the MS-CIM to the MS-PIM.

Emergent technologies (WP 5)

The purpose of this task was to exploit existing technologies and knowledge in order to fulfil the requirements in characterization and improvement of machining systems. Existing and state of the art measurement technologies like laser interferometer and LDBB were used in order to measure geometric, kinematic and load induced errors. A modelling methodology was developed and implemented for predicting the errors of an actual toolpath to be executed by a machine (Laspas, 2014, Szipka, 2015 and Archenti, 2014). The measurement results were used as input for the models. Two modelling methodology approaches, the top-down and bottom-up, were developed as illustrated in Figure 8.

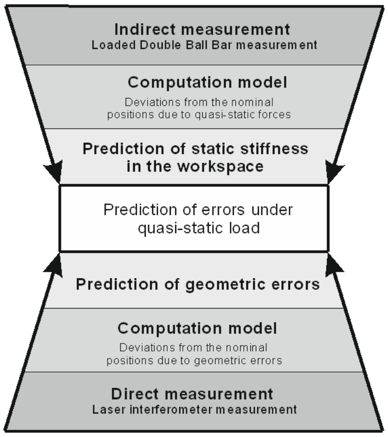


Figure 8. Bottom-up and top – down modelling approaches

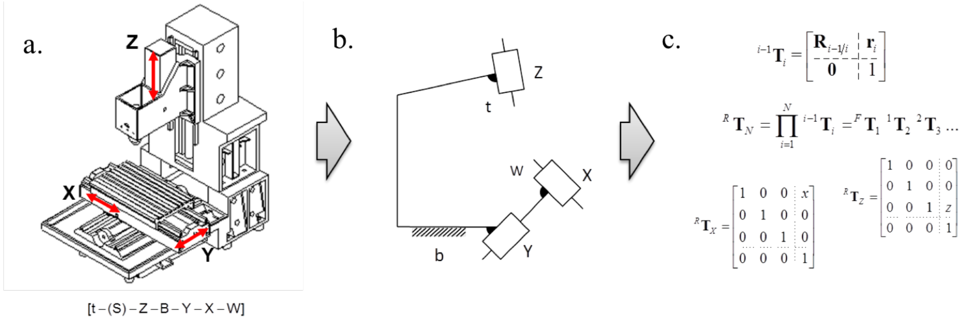


Figure 9. The bottom-up modeling approach steps. a) the kinematic configuration of the machine tool is identified, b) a simplified geometric model of the rigid kinematic structure and the respective joints and joint motion directions are defined, c) HTMs are used to model the rigid body motions.

The bottom-up modelling approach is based on homogeneous transformation matrices (HTM) for creating a geometric error model based on the kinematic structure of the machine tool, including geometric errors of each individual axis. The model computes the relative deviation between the tool and the workpiece due to the error stack-up of the axes within the serial kinematic chain and predicts the errors in a given toolpath that the machine tool is programed (Figure 9a-c). Laser interferometer measurements of the individual geometric errors of a machine were used as input for populating the geometric error model. In the top-down modelling approach the aim is to predict the variation of the static stiffness in the workspace of a machine tool. LDBB is used to measure at four different positions within the machines workspace the superposed errors (kinematic and load induced). In this case the aim of this computational model is to decompose the indirect measurement data and use them as inputs and calculate the static stiffness at different points of the workspace (Figure 10).

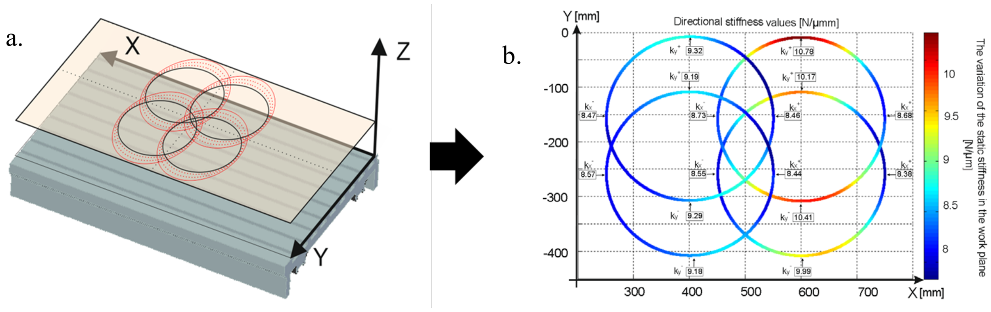


Figure 10. a) the four positions where the LDBB were performed, and b) the variation of stiffness due to the spatial variations (axes positions) in the selected measurement plane.

Finally, as a verification step a cylindrical workpiece was machined and the programmed circular toolpath was calculated by the geometric error model of the machine to compare the results (Figure 11).

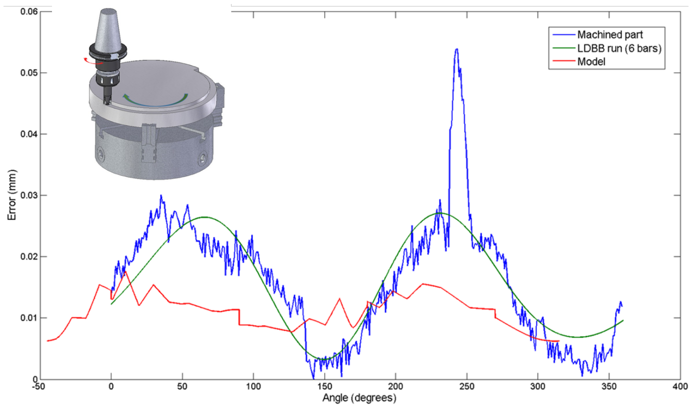


Figure 11. Comparison of the errors of the machined part, the geometric error model and the LDBB measurement. In red are the predicted deviations due to geometric errors of the selected circular toolpath. In blue are the deviations from the nominal toolpath as measured in a CMM on the actual machined part. In green is the smoothed error trace from the LDBB at a load of 6 bars.

As the model did not take into account the stiffness of the machine, the resulted calculated path was varying compared to the measured deviations of the actual machined part geometry. As a comparison in Figure 11 an LDBB measurement (fitted) at a comparable force level is included showing a satisfactory agreement between machined and measured errors.

Deliverable from WP 5: Model, based on the ELS concept defined in WP 2, for MS-CIM linked to MS-PIM assessment of kinematic – load dependent errors in machine tools, analysis of the success of the predictions for one test piece.

5.1 Delivery to FFI-goals

The executed RTD activities are in line with the FFI's programme in sustainable manufacturing. Developments contributes to strengthen the knowledge-based production in Sweden by producing high value-added products offering technological, economic and environmental advantage to the companies, customers and the society.

In the process planning activity, optimal selection of machines, processes and parameters based on CIMs will contribute to essential improvement of the MS and manufacturing performance by: (i) Increasing flexibility by minimizing the need for rework; Increased material removal rate (MRR) and by this productivity; (ii) Improved part quality; (iii) Efficient use of manufacturing system to process new materials that enables production of innovative components for next generation environment friendly vehicles; (iv) Reducing waste and energy consumptions. Using CIMs in maintenance programmes will support activities for: (i) Avoidance of sporadic stops; (ii) Prolonged life of the machine and machine components; (iii) Re-use of machine-tool components by preserving their functions through capability-based maintenance. (technical reports)

7. Dissemination and publications

6.1 Knowledge and results dissemination

Results from the project will be utilized trough collaboration with various partners. A natural way to address higher TRL is to collaborate with the Powertrain Manufacturing for Heavy Vehicles Application Lab - a collaboration between KTH, Fraunhofer and RISE. For instance, an ongoing project named CHARMS Characterisation of Machining systems are addressing issues with robust and flexible manufacturing. To further strengthen the scientific level of the COMPIT concept on machining system capability research, collaboration has been established within the Swedish Initiative for Excellence in Production Research - XPRES at KTH. Furthermore, results from the project will (and has) be been disseminated trough various channels e.g.: training courses for industrial practitioners (WP 6 activity); KTH DMMS and Chalmers MCR member's days; the Swedish Manufacturing R&D cluster conference; ongoing FFI projects DAIMP and OFP4p.

One important task of the COMPIT project was development of training material and preliminary run of trainings together with the industrial partners. A four-hour lecture was design, starting with basic machine tool design and operational usage, machine tool characterisation, static and dynamic aspects and finally ending with CNC Integrity Tracing System. A sum of 20 technicians participated. At the end of the project each partner has access to the curse material.

6.2 Publications

Scientific thesis:
Österlind T., (2013), An Analysis of Machining System Capability and Its Link with Machined Component Quality, Licentiate thesis, KTH Royal Institute of Technology, Stockholm, Sweden.

Scientific publications (12):
Österlind T., Kari L., Nicolescu C. M., (2017), Analysis of stationary displacement patterns in rotating machinery subject to local harmonic excitation, Journal of Sound and Vibration.
Vogl, W. G., Donmez, A., Archenti, A., (2016), Diagnostics for geometric performance of machine tool linear axes, CIRP Annals - Manufacturing Technology.
Laspas, T., Archenti, A., (2016), Investigation of multi-axis system static and kinematic characteristics, in: 7th Swedish Production Symposium, Lund, Sweden.

Szipka, K, Laspas, T., Archenti, A., (2016), Prediction of machine tool errors under quasi-static condition, in: 7th Swedish Production Symposium, Lund, Sweden.
Eynian M, A. Wretland, (2016) Sensitivity of Axis Tracking Errors of Machine Tools to Tool Wear in Drilling, in: 7th Swedish Production Symposium, Lund, Sweden.
Rastegari, A., Archenti, A., (2016), Online Condition Monitoring of Gas Circulation Fans in Hardening Process, International Congress of Condition Monitoring and Diagnostics Engineering Management COMADEM, XI'AN, China.
Cedergren, S., Frangoudis, C., Archenti, A., Pedersen, R., Sjöberg, G., (2015), Influence of work material microstructure on vibrations when machining cast Ti-6Al-4V, International Journal of Advanced Manufacturing Technology.
Dapero, A., Archenti, A., (2015), Identification and analysis of linked systems' dynamic accuracy, proposal of a measurement approach and instrumentation, Journal of Machine Engineering, Vol. 15, No. 3, pp. 90-105.
Nicolescu, C.M., Frangoudis, C., Semere, D., Archenti, A., Rashid, A., (2015), New paradigm in control of machining system´s dynamics, Journal of Machine Engineering, Vol. 15, No. 3, pp. 117-137.
Archenti A., (2014), Prediction of part accuracy from machining system capability, CIRP Annals - Manufacturing Technology.
Beno, T, et.al. (2013) The Use of Machine Tool Internal Encoders as Sensors in a Process Monitoring System, International Journal of Automation Technology, 410-417.
Österlind T. Frangoudis C., Archenti A., (2013), Operational modal analysis during milling of workpiece, fixed on a stiffness controllable joint, J. Eng. Mech., vol. 13, no. 2

Master thesis reports (9):
Montalban, L. (2016), Evaluation of a contactless excitation and response system (CERS) for process planning applications, KTH Royal Institute of Technology, Master level.
Grigoriadis, I. (2016), Evaluation of a Contactless Excitation and Response System for Condition Based Maintenance, KTH Royal Institute of Technology, Master level.
Ramanaiah, V. H. (2016), Relation between process capability indices and geometric errors of machine tool, KTH Royal Institute of Technology, Master level.
Szipka, K. (2015), Modelling and measurement of machine tool static and quati-static behaviour, KTH Royal Institute of Technology, Master level.
Hansson, A. (2016) Detection of tool wear in drilling based on axis position signals, University West, Trollhättan.
Sturacci, J. (2015), Modelling of machining system dynamic behaviour, KTH Royal Institute of Technology, Master level in aeronautical engineering.
Liu, Y. (2015) Effect of CNC axis movement on the surface roughness in milling, University West, Trollhättan.
Laspas, T. (2014), Modeling and measurement of geometric error of machine tools, KTH Royal Institute of Technology, Master level.
Dapero, A. (2014), Identification and analysis of machining systems dynamic behaviour, KTH Royal Institute of Technology, Master level.

Technical reports (10):
Österlind T., Laspas T., Archenti A., (2016), Analysis of CFRP machining in Zimmermann FZ30 – Cutting forces and surface inspection, SAAB Aeronautics, Linköping, Sweden.
Laspas, T., Archenti, A., (2016), Quasi-static accuracy of STARRAG STC 1800 under loaded conditions, SAAB Aeronautics, Linköping, Sweden

Österlind T., Laspas T., Archenti A., (2016), Zimmermann FZ30 & FZ33 comparison report, SAAB Aeronautics, Linköping, Sweden.

Österlind T., (2016), Quick investigation of tool wear from machining of CFRP, SAAB Aeronautics, Linköping, Sweden

Österlind T., (2016), Surfaces from milling in FZ33, straight cutting, SAAB Aeronautics, Linköping, Sweden.

Laspas, T., Archenti, A., (2015), Evaluation of Quasi-Static deviations of Machine Tools, Scania CV AB, Södertälje, Sweden.

Laspas, T., Österlind, T., Archenti, A., (2015), Analysis of CFRP machining in Zimmermann FZ33 – Cutting forces and surface inspection, SAAB Aeronautics, Linköping Sweden.

Österlind T., Laspas T., Archenti A., (2015), Analysis of CFRP machining in Zimmermann FZ33 – Cutting forces and surface inspection, SAAB Aeronautics, Linköping, Sweden

Laspas, T., Österlind, T., Archenti, A., (2014), Evaluation of the Quasi-Static and Kinematic Accuracy of Zimmermann FZ 33, SAAB Aeronautics, Linköping Sweden.

Laspas, T., Österlind, T., Archenti, A., (2014), Evaluation of Quasi-Static- and Kinematic Accuracy and Dynamic Deformation of Zimmermann FZ 33 and FZ30, SAAB Aeronautics, Linköping Sweden.

8. Conclusions and future research

The uniqueness of the COMPIT platform lies in the fact that not only it integrates the machining system capability and performance assessment into one, allowing an understanding of their mutual interactions, but also the assessments are closest possible to the operational conditions (Laspas, 2014, Szipka, 2015, Archenti, 2014). The project has resulted in further development of test instruments and methodologies, validated through industrial case studies, which will be available for implementation in industry. By using these tools, CERS (Montalban and Grigoriadis, 2016), LDBB (Laspas and Archenti, 2016) and CITE (Eynian and Wretland, 2016), companies can define and select MS-CIMs that best relates to the requirement specification of their products (e.g. quasi-static stiffness). By using the CIM-PIM relational model, users can understand how the variations in the parameters describing the machining system are related to the variations of system performance (Laspas, 2014, Szipka, 2015 and Archenti, 2014). The use of the CIM-PIM concept will enhance the understanding of industrial practioners and researchers about interactions between the machining system capability and performance and help them in developing better performance improvement solutions at a faster pace.

Future research on the COMPIT concept will include thermal effects and uncertainty assessment of the measurements and modelling.

The CERS and LDBB instruments, was brought into the COMPIT project as novel technologies to be exploited in industrial environments, has been granted three innovation grants trough KTH Holding AB (VFT-1 fas 0 and fas 1 and KTH Innovation pre-incubation program) and one re-patenting (patent No. 15155654.5 – 1558 Method and test assembly for determining machine parameters). One of GKN´s supplier of measurement equipment showed interested in the CITE system. A non-disclosure agreement was signed by

University West (in agreement with COMPIT members) and a discussion on collaboration has started.

9. Participating parties and contact person

Following partners and persons has been involved in the COMPIT project (Table 1).

Table 2. Partners and their participation in different work packages.

Party	**Roll and area of responsibility**	**Researcher**
KTH DMMS	Project coordinator and secretary in the steering committee. Responsible for COMPIT scientific architecture and framework development. Work package leader for WP1, WP2, WP3. Task leaders for 2.2-2.5, 3.1, 3.2, 6.4. Technical development role in all other work packages.	▪ Andreas Archenti, Associate Professor, project manager, archenti@kth.se ▪ Mihai Nicolescu, Professor ▪ Lorenzo Daghini, PhD ▪ Tomas Österlind, PhD student ▪ Theodors Laspas, PhD student
University West	Steering committee member. Work package leader for WP4. Task leaders for 2.1, 3.3, 6.3	▪ Mahdi Enyan, PhD ▪ Tomas Beno, Professor ▪ Jari Repo, PhD
Scania CV AB	Steering committee member. Industry partner that participates with experts and provides case studies. Work package leader for WP5. Task leaders for 4.1, 5.1, 6.1	▪ Anders Berglund, PhD ▪ Mikael Hedlind, PhD ▪ Anders Ramström
AB Volvo	Steering committee member. Industry partner that participates with experts and provides case studies. Work package leader for WP6. Task leaders for 4.2	▪ Danfang Chen, PhD ▪ Ali Rastegari, industrial PhD student ▪ Jan Eriksson ▪ Stefan Köhler
GKN Aerospace Sweden AB	Steering committee member. Industry partner that participates with experts and provides case studies. Task leaders for 6.2	▪ Anders Wretland ▪ Stefan Cedergren, PhD
Leax Falun AB	Steering committee member. Industry partner that participates with experts and provides case studies. Task leaders for 4.3	▪ Eric Nordgren ▪ Rickard Isaksson
SAAB Aeronautics	Steering committee member. Industry partner that participates with experts and provides case studies. Task leaders for 4.4	Mikael Nilsson Mikael Karlsson Johan Björklund