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On-Machine Measurement Use Cases and Information for Machining Operations

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Abstract

Thorough and unambiguous definitions of a broad set of on-machine measurement use cases and information are offered. Relevant in-situ and off-machine measurement use cases are also described in some detail, due to their close relationship to on-machine measurement. The use cases are defined to expose a comprehensive scope of information useful to manufacturing information standards bodies. Activity diagrams for on-machine measurement are presented which help clarify the use cases and information elements required for on-machine measurement. Due to the lack of definitional consensus on terms and definitions for on-machine measurement in the literature, a broad scope of terms required by the numerous and varied types of quality measurement use cases commonly performed on or around machine tools are precisely defined, while seeking to remain faithful to definitional usage common in industry and academia.

Key words

On-machine measurement; in-process measurement; in-situ measurement; off-machine measurement; in-line measurement; pre-process measurement; post-process measurement; digital thread; information modelling; information standards; manufacturing information standards; manufacturing quality measurement; dimensional metrology; interoperability standards; MTConnect; Quality Information Framework

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1 Introduction

The application of quality operations at all points in the manufacturing process has a long history [1]. Manufacturers worldwide continue to perform quality measurement activities on parts and equipment at select points throughout the product lifecycle, wherever and whenever it seems best to do so, optimizing throughput, quality, cost, safety, and responsibility [2-5]. Measurements performed within the physical workspace of a machine tool, which we define as on-machine measurement (OMM), have been shown to reduce machining time, scrap, and other costs for certain important use cases, for example, where there are high cost materials and complex parts [3, 6]. Section 2 will unpack this issue. We have adopted a depth-first approach, and therefore focus on milling machine operations.

Since OMM operations are ubiquitous, relevant manufacturing information modeling standards organizations [7, 8] will benefit from a broad range of information definitions and semantics that are accurate, relevant, comprehensive, and detailed [9], ensuring that OMM-relevant information will find its way into the relevant standards [10, 11]. A careful development and study of OMM use cases will help to expose this information.

Two standards groups, one in machining – the MTConnect Institute [7] – and one in metrology – the Dimensional Metrology Standards Consortium (DMSC) [8] – have formed a joint working group that is actively identifying and modeling OMM information. The MTConnect Institute's MTConnect specification [10] and the DMSC's ANSI Quality Information Framework (QIF) standard [11], both defined in XML Schema [12], are currently providing cost saving benefits through their implementation in many manufacturing operations worldwide.

This research offers detailed activity models for a broad set of OMM use cases, exposing information required to execute each use case. For example, information elements essential to OMM, such as machine tool offsets, machining code modifications for OMM, raw stock (or workpiece) measurements, cleaning and cooling system commands, swarf measurements, temperature measurements, humidity measurements, and interim part models, are identified in Section 6 as necessary to many OMM use cases. All figures in this document utilize the iDEF0 system activity modeling methodology [13], and these models of OMM activity constitute a single integrated hierarchical model.

The OMM processes described in Section 6 have been implemented to varying degrees by a wide variety of manufacturers and solution providers. Given the lack of a widely adopted standard information model, the same semantic information for OMM is written in multiple proprietary digital languages (often called "formats"), causing a confusion of language that is costly to both end users and solution providers. This claim of the high cost of multiple languages (either proprietary or standard) is described in Section 4.

Our focus is on OMM, since our goal is to provide information elements helpful to standards groups like DMSC and MTConnect. However, some other use cases, namely, off-machine and in-situ, have unique information that should be modeled in standards like DMSC and MTConnect. These additional use cases also provide a broader context of the full scope of measurement in a manufacturing plant.

The National Institute of Standards and Technology (NIST) has generated a similar set of activity models for manufacturing use cases, called the SIMA (Systems Integration of Manufacturing Applications) Reference Architecture. SIMA thoroughly models an ambitious scope of manufacturing activities, but at a higher level of abstraction than this OMM research. Much of the OMM model connects with the SIMA model through SIMA's "Control Equipment" activity [14].

This paper is structured as follows. Section 2 presents arguments for the value of OMM along with answers to objections. Section 3 provides terms and definitions for OMM. Section 4 presents an argument for the development and broad use of OMM digital thread standards. Section 5 presents the research plan guiding our approach. Section 6 presents a set of OMM use cases along with the information requirements for input to the standards bodies. Sections 7 & 8 present use cases that are closely related to on-machine, namely in-situ and off-machine. Finally, Section 9 summarizes the paper and suggests future efforts.

In order to provide context, in-situ and off-machine measurement use cases are described in some detail in this paper, because of their temporal, spatial, and semantic resemblance to OMM. Use cases and information for off-machine post-process measurement receive negligible attention, since it has received much attention in the literature [15].

2 The challenges and benefits of on-machine measurement

When machine tools were less accurate and ubiquitous methods for controlling the environment in and around the machine tool were rare, there was a veritable prohibition on performing probe-on-spindle, on-machine, and in-process measurement (IPM). Manufacturers are now not prohibiting OMM, but there is persistent suspicion of its value and/or ignorance of how to perform OMM successfully. Arguments given for this suspicion include 1) measuring with the same tool (axes, spindle, and frame) with which one is machining seems manifestly suspect, 2) measuring on-machine is non-value-added and reduces productivity, since it takes time away from machining operations, 3) writing probing routines is typically difficult and time consuming, and 4) the machine tool environment is so unstable and unpredictable in terms of humidity, temperature, sticky cutting fluid, and unpredictable swarf, one can never be confident that an on-machine measurement will produce accurate measurements [2-4, 6, 16-18]. Answers to these objections include:

- With increasingly accurate machine tools, one can now calibrate a machine tool, measurement probes, and spindle at will, prior to measurement, if required, and reduce measurement uncertainty
- The cost of making a mistake while machining a critical feature will sometimes constitute a larger cost than the loss of machining time caused by on-machine measuring

- The machining of large size, tight tolerances, high material cost (*e.g.*, titanium and composites), and/or highly malleable parts tends to favor performing OMM
- Accurate probing macros and software routines are available from several software vendors
- Probing on spindle is profitably employed a) in-process intermittent to send data to the machine controller monitoring critical conditions, *e.g.*, errors, tool breakage, and physical dislocation of the part, and b) off-machine post-process while the part is still fixtured in the machine, augmenting if not replacing a separate coordinate measuring machine (CMM)
- Certain types of errors which are hard to eliminate via machine tool maintenance/certification are easily discovered via in-process measurement, *e.g.*, common problems during machining, like machine deflection/distortion, tool wear, and vibration, will all be absent during measurement
- The removal of swarf and cutting fluid has been successful with various cleaning systems and techniques, *e.g.*, tombstone[1] fixtures and part cleaning baths.

In general, OMMs are more error-prone than measurements on a stand-alone CMM in an environmentally controlled area. The machining environment suffers from widely varying and uncertain temperature, humidity, and particulate matter conditions, all of which challenge accurate OMM. Controlling this variability can be difficult, costly, and/or time-consuming. When a machine tool goes out of calibration for machining, it simultaneously goes out of calibration for measurement. In contrast, measurements on CMMs are often performed in a particle-free environment with stable temperature and humidity, all of which decrease measurement uncertainty. For critical industries, like aerospace, accurate CMMs provide documented evidence for the compliance of the manufactured product to accepted standards.

A metrologist considers carefully the details of each measurement and its environment, when deciding which features and characteristics should be measured on-machine and which should be measured on a stand-alone CMM in an environmentally controlled area. For example, if the cost of delivering a faulty part to the customer is sufficiently high, *e.g.*, the part is very expensive or failure in its functional role would be catastrophic, then an off-machine post-process measurement may need to be performed, even though OMM may also be performed on certain part features and characteristics.

Nonetheless, there are several circumstances that favor the use of OMM. The cost of faulty parts is known to increase exponentially along the manufacturing process timeline. Therefore, OMM may improve product quality, customer satisfaction, and profitability, if the OMM is sufficiently accurate and the cost of performing OMM is less than the cost of faulty parts. Modern high-quality machine tools can also achieve and maintain very precise performance tolerances, and therefore can produce accurate measurements, when accompanied with thoughtful measurement practices. OMM adds benefit by reducing wasted machining time and scrap parts. OMM avoids the "second fixation problem of the

[1] Tombstone fixtures allow the temporary removal of a part or stock/workpiece from the machine tool workspace for cleaning or measurement operations and then back to the machine tool workspace for further operations, with repeatable relocation of part or stock within the machine tool coordinate system.

workpiece," when moving the part to a CMM [19]. OMM includes increased throughput from existing assets, which defers capital expenditure, reduces sub-contract and overtime bills, and allows additional business without increasing resources. Another benefit of OMM is automation and reduced human intervention which, in general, improves tool setting[2] and measurement accuracy, reduces direct labor costs, enables redeployment of staff into proactive engineering roles, and increases repeatability versus the generally increased variability gotten from manual methods, *e.g*., avoids manual 'cut and measure' activities and errors manually keying in height offsets, which can cause tool crashes. OMM generally enables reduced rework, concessions[3], and scrap, which improves conformance and consistency, lowers unit costs, shortens lead times. Finally, OMM enhances system capability, offering customers state-of-the-art capabilities, options to take on more complex work, and satisfying customer demands for traceability [2].

Using machine tools for measurement and machining requires machine tool geometric accuracies sufficient to measure a part within all the tolerances specified for that part, otherwise in-process measurement will be wasted, and the parts may not be machined to tolerance. The machine tool must be sufficiently monitored over time and calibrated to ensure that it can maintain part tolerances within those specified by the customer.

3 Terms and definitions for on-machine measurement

Terms commonly employed for manufacturing measurement activities, *e.g*., in-process, on-machine, process-intermittent, in-situ, and in-line, appear copiously in the academic and trade literature, along with qualifying terms like measurement, verification, validation, probing, metrology, and gaging. These terms are sometimes combined to form descriptive phrases. Accurate, consistent, and unambiguous definitions of manufacturing measurement terms and phrases are largely non-existent in English dictionaries (including at wikipedia.org) and in standards documents. Consequently, we turned to the academic and trade literature for insight on manufacturing measurement taxonomy and terminology.

In both the academic and trade literature, authors only sometimes explicitly define their use of manufacturing measurement terminology. Even when definitions are explicit, definitions may still vary from author to author [2-6, 15, 18, 20-36]. Dimensional measurements of all types of features on a part fixtured on a machine tool are called either IPM or OMM, and therefore, IPM and OMM are largely used interchangeably, no matter whether cutting operations are interrupted to perform a measurement with probe on spindle or not. Standards organizations have not defined a standard specifically for OMM taxonomy, though ISO 230-10 [37] does address several OMM use cases. As a result, we were not able to depend on dictionaries, the literature, or standards as a complete source for accepted definitions.

Given the imprecise definitional state of OMM, it is *essential* to this research to provide precisely defined OMM terms that clarify semantics and expand the definitional space.

[2] An operation to accurately measure length and diameter of various cutting tools and other characteristics such as missing cutting edges, cutting edge radius, etc.
[3] Not fixing an error because the error is either not critical or not cost effective to fix, which is a different action from rework or scrap.

We've chosen to classify measurements, performed on or near the machine tool, in terms of the *where*, *when*, and *why* of manufacturing measurement, which can also be expressed as, the *location in space*, the *location in time*, and the *type* of the measurement, respectively. This choice is made because these terms can be made to form orthogonal (non-overlapping) dimensions, *e.g.*, *where* a measurement is performed will not constrain *when* it is performed, which in turn will not constrain *why* the measurement is performed. The *what* and *how* of measurement can provide an even more thorough definition of a measurement; nonetheless, *where*, *when*, and *why* will be adequate for this research.

Terms and definitions indicating *where* the measurement occurs:

- *On-machine*: A measurement performed where the measurement target is located within the machine tool workspace and the measurement device is within or nearby the machine tool workspace
- *In-situ*: A measurement performed where the measurement target and measurement device are both located outside, but nearby, the machine tool workspace, and the measurement target may or may not be mapped into the machine tool coordinate system
- *Off-machine*: A measurement performed where the location of the measurement activity is completely disassociated from the location of the machining process

Terms and definitions indicating *when* the measurement occurs:

- *At-design*: A measurement planning activity performed before any physical measurement begins and often prior to part approval, when part design and part production may still be malleable. It may involve part model simulation, including expected tool paths for different feeds and speeds of a machine tool and for different machine tools, and where the simulation may consider all the tool data, thermal expansion, and machine kinematic information
- *Pre-process*: A measurement performed prior to any machining operation, but after measurement design, and performed on elements such as fixtures, stock, machine tool, cutting tools, probe/tool setting devices, and measurement probes to enable in-tolerance machining
- *In-process*: A measurement performed after machining begins and before the part is removed from the fixture, without cessation/pause of cutting operations[4]
- *In-process-intermittent*: A measurement performed after machining begins during a cessation of machining operations, before the part is finally removed from the machine tool fixture
- *In-line*: A measurement performed on a part or assembly, between production operations in the context of a continuous operation, manufacturing cell, or a multi-stage operation
- *Post-process*: A measurement on finished product at the end of the manufacturing process for that product, prior to delivery to the customer or prior to the next operation in an assembly line, whether it is a monolithic part or an entire

[4] While it is logically possible that a part in-process could be taken off the machine tool and measured on a CMM in an environmentally-controlled room and brought back onto the machine tool to finish the machining, such a use case is outside our scope, and is also performed only for special situations.

assembly. Post-process measurements typically have one or more of the following attributes: an environmentally controlled location (*e.g.*, temperature, air quality, humidity), a very accurate measurement operation (*e.g*., accurate probes, precise CMMs or gages), and is frequently required for part acceptance by the customer

Term and definition indicating *why* or *for what purpose* the measurement occurs:

- *Measurement*: The process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity [38]

Given the terms and definitions proposed above, we can construct different combinations of terms to form precisely defined, non-overlapping measurement types that cover the definitional space of on-machine measurement required by this research.

Table 1: Measurement types and definitions

Type	Definition
On-machine, pre-process	A measurement performed after measurement design and prior to any machining operations, where the measurement target is located within the machine tool workspace and the measurement device is within or nearby the machine tool workspace
On-machine, in-process	A measurement performed after cutting begins, before the part is finally removed from the machine tool fixture, without cessation or pause of cutting operations, where the measurement target is located within the machining workspace and the measurement device is within or nearby the machine tool workspace
On-machine, in-process-intermittent	A measurement performed after cutting begins, before the part is finally removed from the machine tool fixture, during a cessation of cutting operations, where the measurement target is located within the machining workspace and the measurement device is within or nearby the machine tool workspace
In-situ, pre-process	A measurement performed prior to any machining operations, where the measurement target and measurement device are both located outside, but nearby, the machine tool workspace, irrespective of whether the measurement target is mapped to the machine tool coordinate system
In-situ, in-process-intermittent	A measurement performed after cutting begins, before the part is finally removed from the machine tool fixture, during a cessation of cutting operations, where the measurement target and measurement device are both located outside, but nearby, the machine tool workspace, irrespective of whether the measurement target is mapped to the machine tool coordinate system
Off-machine, at-design	A measurement performed where the location of the measurement activity is completely disassociated from the location of the machining process, before any machining or physical measurement begins and often prior to part approval, when part design and part production may still be malleable

Off-machine, pre-process	A measurement performed where the location of the measurement activity is completely disassociated from the location of the machining process, before any machining or physical measurement begins, when part design is fixed but part production may still be malleable
Off-machine, in-line	A measurement performed where the location of the measurement activity is completely disassociated from the location of the machining process, where the measurement is performed between production operations on a part or assembly in the context of a continuous operation, manufacturing cell, or a multi-stage operation
Off-machine, post-process	A measurement performed where the location of the measurement activity is completely disassociated from the location of the machining process, and after all machining on the part is complete, where the measurement typically has one or more of the following attributes: an environmentally controlled location, a very accurate measurement operation, and is required for part acceptance by the customer

When a machine tool has an enclosed workspace, definition of "machining workspace" is easy to define. However, when the workspace is not enclosed, the precise borders of the machine tool workspace may be harder to define. However, what generally happens is that the object to be measured is clearly removed from the machine tool workspace, which would be considered either an in-situ or off-machine measurement, depending on other factors.

An in-line measurement is performed between machining or assembly stations, which may or may not be performed on a CMM in an environmentally controlled location, but typically is not. At design measurements, in-line measurements, and post-process measurements are all important, but are not in scope for this research, though some of these measurements are included in the figures for context. A manufactured part will at times go on to other plants for further machining and assembly, but that use case is also not in scope.

4 The benefits of information exchange standards

The key intention of this research is to discover, precisely define, and recommend standardizable OMM information for use in digital manufacturing information standards. The value of correct, complete, unambiguous, open, freely available, and widely adopted information standards to enable faster, better, cheaper products is substantial, a claim we now summarize [39-41]. Computer-controlled equipment brought benefits of speed and accuracy to all kinds of manufacturing operations, but also brought a confusion of language to the shop floor, with multiple software vendors using different terms and semantics to describe the same operations. The cost of language confusion is evidenced in many costs, including non-value-added translation, information quality loss, lack of freedom of product choice, agility constraints, reduced competition, reduced innovation, increased training fees, increased license fees, unnecessary software development, information access fees, product delay, and high dependence on vendor viability. On the other hand, the creation and broad adoption of correct, complete, unambiguous, open, and freely available specifications of digital (computer-readable) manufacturing information, like MTConnect and the Quality Information Framework (QIF), can greatly reduce these costs. The substantial benefits of information exchange standards are obviously not unique to OMM use cases but apply to any interface involving digital information between system operations in manufacturing.

5 Research plan

A thorough set of use cases for on-machine measurement (OMM), sufficient to expose information exchange requirements, is presented. The "machine" is a computer numerically controlled (CNC) machine tool and the measurement device may be the CNC machine tool itself, or a separate measurement device, located on-machine, with focus on milling processes.

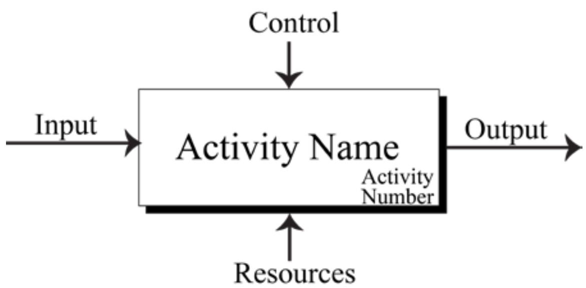

Fig. 1: Format for iDEF0 activities and data

Our goal is to generate a comprehensive set of information elements, consisting of both syntax and semantics. To achieve this goal, we first uncover common use cases found in the trade, academic, and standards literature. Then we develop an integrated set of activity models based on those use cases. The activity models are represented using the iDEF0 modeling method [13], which naturally exposes the required information. The meaning of the various iDEF0 elements is shown in Fig. 1.

Information modeling for dimensional metrology research has been performed by Zhao, et al [15, 42] describing in-process, off-line, and on-machine measurements. Our research builds on Zhao, et al, providing activity models for OMM, a basic manufacturing on-machine measurement taxonomy (Section 3), a thorough set of OMM use cases, and detailed semantic information definitions required by each on-machine measurement use case. This information, both generated and consumed, is intended for representation as a digital model, *e.g.*, XML Schema, in a form compatible with the existing ANSI Quality Information Framework (QIF) standard and the MTConnect open specification.

The goal of this research is to provide OMM information to augment existing information content within information standards like MTConnect and QIF. The MTConnect Institute and the DMSC (developers of MTConnect and QIF) have defined machining terms and measurement terms, respectively. This research is meant to ensure that OMM-related information is identified, unambiguously defined, and utilized in MTConnect and QIF. We recommend the formation of an OMM joint working group to 1) develop required new or modified XML/XSLT (eXtensible Stylesheet Language Transformations) information definitions, 2) define clarifying annotations within the MTConnect and QIF schemas to help software developers realize accurate and timely implementations of MTConnect and QIF, 3) develop user's guides for software developers for using both

MTConnect and QIF, and 4) publish other documents, *e.g.*, in trade magazines, conferences, and archival journals, providing guidance for optimal use of on-machine measurement for each of the various use cases. A valuable ancillary task would be to develop a decision tree to aid manufacturers to determine where and when OMM would be best for their process, starting with machine tool processes.

This work does not claim to be an exhaustive study of all OMM practices of every manufacturer's use of solution provider and vendor product offerings, but instead seeks to cover the field sufficiently to ensure that widely used OMM use cases are documented, as would be sufficient to develop a correct and complete set of OMM digital information definitions, appropriate to the relevant standards, viz., QIF and MTConnect.

6 OMM use cases and information elements

In this section, we present a comprehensive list of on-machine measurement use cases currently in use by manufacturers and solution providers for machine tool operations. The information required to perform each use case and the information generated by each use case is shown in the iDEF0 models and described in more detail in the body of the paper. Activity diagrams associated with the use cases are provided to show the interconnection among the various use cases and to expose information input and output required by the activities. The chosen use cases focus on those most commonly executed by manufacturing and solution providers, including many types of on-machine measurements.

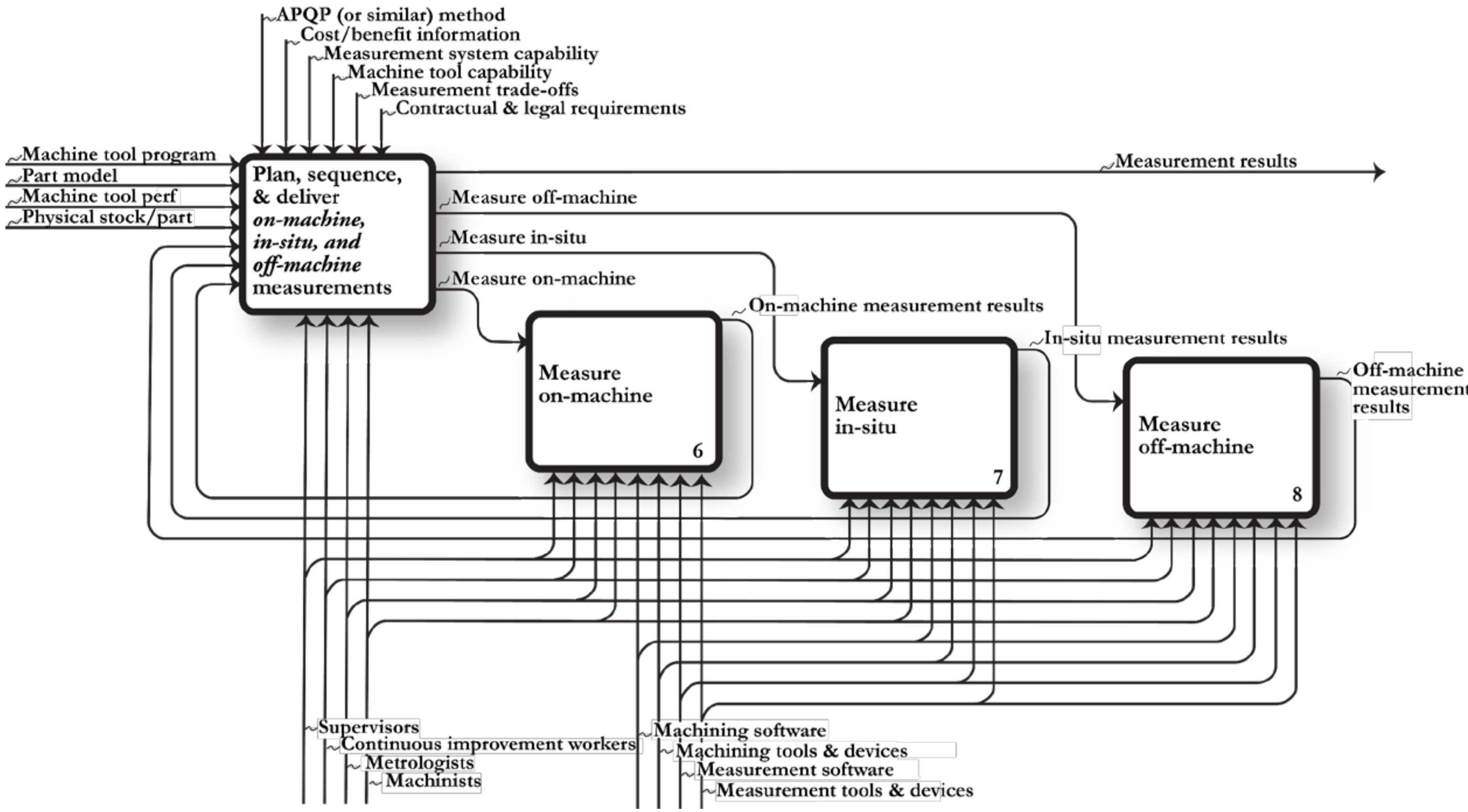

Fig. 2**:** Plan and perform measurements: on-machine, in-situ, and off-machine, described in Sections 6, 7, and 8.

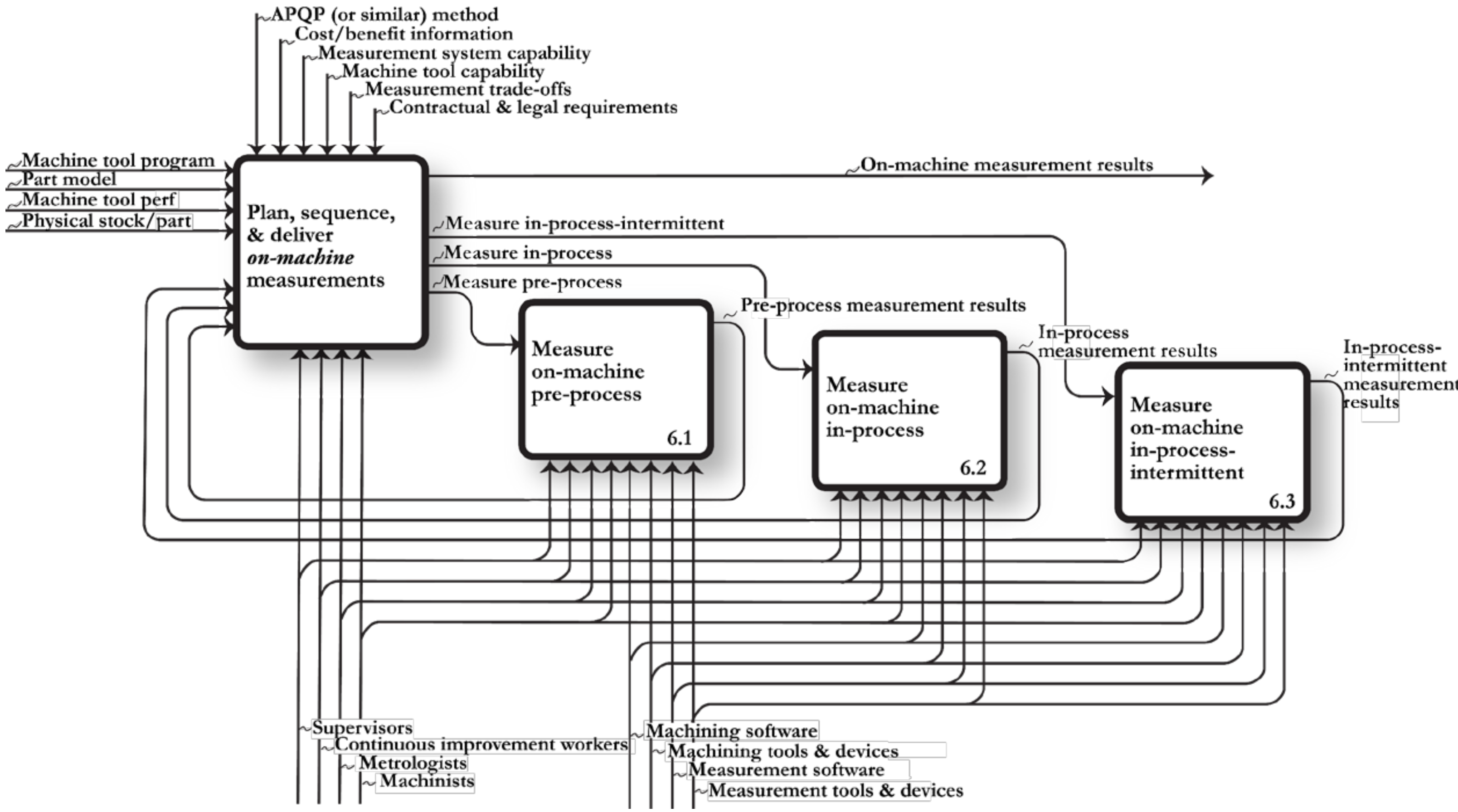

Fig. 3**:** Plan and perform on-machine measurements: a subset of activity 6 in Fig. 2, described in Sections 6.1, 6.2, and 6.3

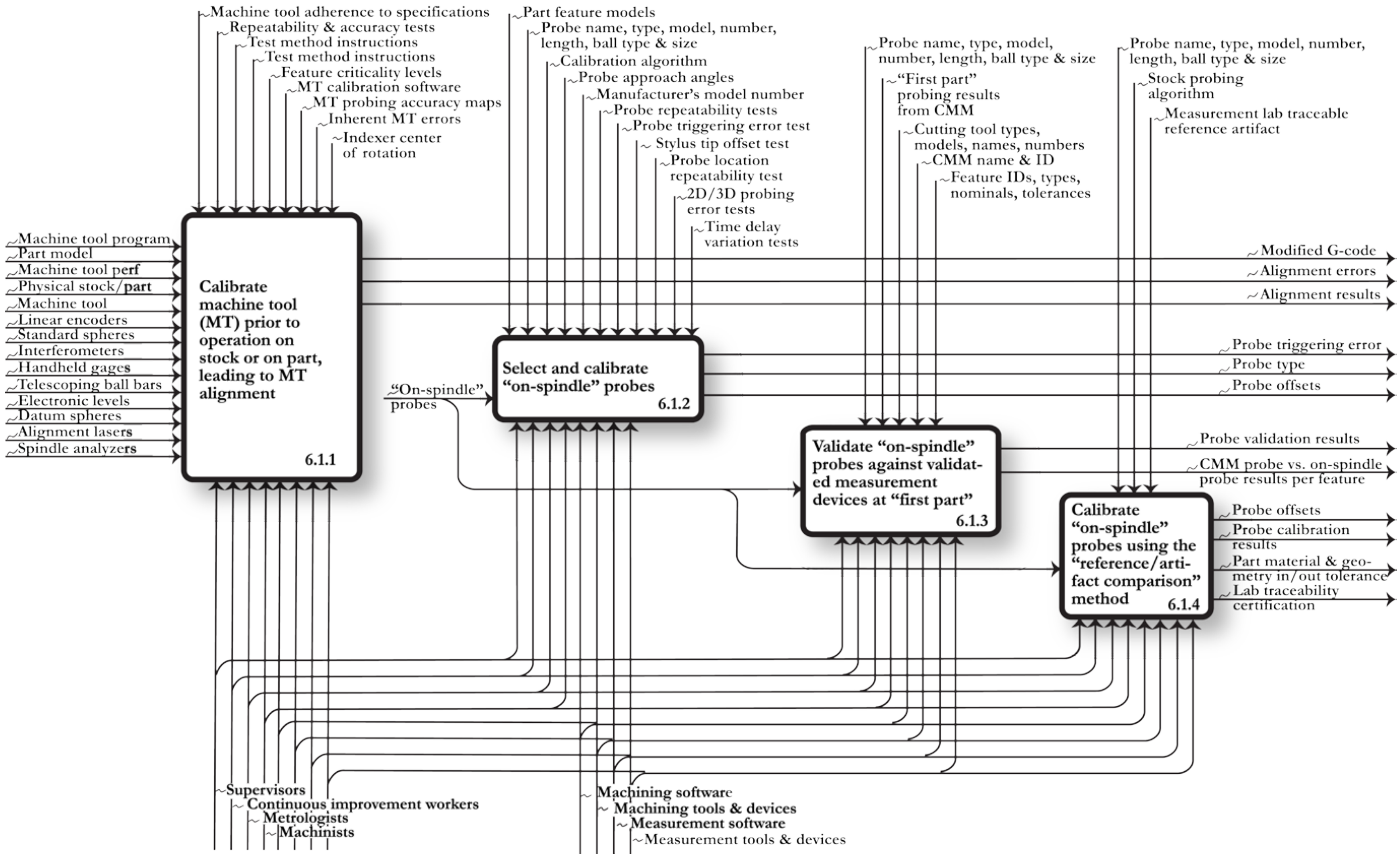

Fig. 4: Measure on-machine pre-process: a subset of activity 6.1 in Fig. 3, illustrating use cases presented below in Section 6.1.1 to Section 6.1.4

6.1 On-machine pre-process measurement use cases

On-machine pre-process measurements are described in Table 1 in Section 3 as *measurements performed after measurement design and prior to any machining operations, where the measurement target is located within the machine tool workspace and the measurement device is within or nearby the machine tool workspace*. This covers any type of measurement performed on any item (*e.g.*, probe, tool bit, spindle, and stock) that could affect the precision and accuracy of subsequent in-process machining or measurement operations.

6.1.1 [On-machine, Pre-process] Calibrate machine tool (MT) prior to operation on stock or on part, leading to part alignment

6.1.1.1 Use case for calibrating a machine tool (MT) prior to operation on stock or on part, leading to part alignment

- Using various items relating to measurement such as linear encoders (optical non-contact and contact), standard spheres (usually one or three of them, in known positions on the machine) [4], handheld gages, telescoping ball bars, electronic levels, datum spheres, alignment lasers, spindle analyzers, interferometers, and special measurement software, ensure multi-axis machine tool performance and adherence to specifications. Here is a short list of calibration measurements for individual performance parameters. We refer the interested reader to a more comprehensive collection of elements required for MT calibration in the ASME B5.54 (2005 R2015) and ASME B5.57 (2012)
    - Machine tool position and geometric errors
    - Spindle axis rotation errors
    - Diagonal displacement error
    - Circular contouring errors
    - Static machine compliance and hysteresis
    - Repeatability performance
    - Straightness and perpendicularity errors in the movement of each machine tool axis
    - Accuracy of the connections between moving elements on the MT, such as, spindle to machine bed, with corrections for thermal variation
    - Location of pivot point on milling spindle for turning operations
    - Roll, pitch, and yaw accuracy
    - Dynamic motion accuracy
    - Magnitude and type of centering errors, form errors, and tracking errors
    - Machine tool probing performance
    - Alignment of any rotary axis, indexer, or fixturing element for positioning and holding part
    - The center of rotation of an indexer or reference points on the fixture

  The output of these checks will be modified machine tool (MT) offsets translated into appropriately modified G-code. Machine tool normal use, as well as the occurrence of machine ‘crashes,’ can cause errors in tool performance. It may take hours to perform these checks, but they ensure the accuracy of future measurements and future machining. The outcome of these checks is to optimize part alignment for machining and improve machine tool probing performance.

- Calibration is often specified as accurate to a certain percentage of the smallest feature tolerance zone on the part, commonly specified at 10%.
- To save time, calibration is sometimes performed only for the planned work envelope [3]

6.1.1.2 Information elements required to calibrate a machine tool (MT) prior to operation on stock or on part, leading to MT alignment

- Various devices: [linear encoders (optical non-contact and contact), standard spheres (can be more than one, in known positions on the machine), handheld gages, telescoping ball bars, electronic levels, datum spheres, alignment lasers, spindle analyzers][5]
- Elements: [components, features, criticality levels for each element]
- Software: [special MT calibration software (standalone or part of package)]
- Positional measurement: [See ISO 230-1 for information elements]
- Dynamic motion measurement: [See ISO 230 series for information elements]
- Location of milling spindle pivot point for a turning machine tool [x, y, z]
- Roll, pitch, and yaw [α, β, γ, and uncertainties for each axis: $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$]
- Inherent MT errors: [centering, form, and tracking in both magnitude and type of error]
- Machine tool probing accuracy: a map of accuracies (Δx, Δy, Δz) for different locations (x, y, z) and orientations (u, v, w)
- Machine tool adherence to specifications: [List of specifications with array of yes/no for each specification]
- [Alignment (x, y, z) and alignment errors (Δx, Δy, Δz) for each of the following: rotary axis, indexer[6], and fixture]
- [Center of rotation of an indexer: (x, y, z)]

6.1.2 [On-machine, Pre-process] Select and calibrate probes on the MT's spindle

6.1.2.1 Use case for selecting and calibrating probes on the MT's spindle

- Select the probe or probes best suited for the task. Common machine tool probes typically have ≤ 1 micrometer probing repeatability. In simpler applications, these probes are used to measure a location or a size of a part [43]. Strain gage probes eliminate lobing and are good for measuring locations on parts with complex surfaces.
- On-machine probe types, model, and number for full OMM use case description need to be recorded.
- Perform probe calibration according to instructions from the manufacturer [34].
- Perform probing repeatability tests for single-point surface measurement, a circle center location, or sphere center location as found in [37]

[5] Bracketed quantities are the actual information elements
[6] Reference points on the fixture

- Perform “stylus tip offset test” as described in [37]
- Perform “ setup and procedure” [37]
- Perform “2D and 3D probing error tests” [37]
- Perform “time delay variation tests” as described in ISO 230-10 2016. These tests provide measurements of stylus tip sensitivity for machine tool vibration [37].

6.1.2.2 Information elements required to select and calibrate probes on the MT’s spindle

- Probe IDs, including elements such as: manufacturer, manufacturer’s probe types, generic probe types, serial numbers, stylus tip types, stylus tip sizes, probe lengths, speed limits, +/- linear accuracy for (x, y, z)
- Measurement devices, including devices such as: linear encoders (optical non-contact and contact), standard spheres (may be more than one, in known positions/orientation on the machine), handheld gages, telescoping ball bars, electronic levels, datum spheres, alignment lasers, spindle analyzers
- Information required by stylus tip offset test, including spindle axis average line, reference ring bore axes, machine tool coordinate system, workpiece coordinate system, and stylus tip offset [37]
- Information required by probing tool location repeatability test, including ring bore axis line, ring top surface plane, and center point and machine tool coordinate system z-axis line for 10 distinct locations of the probing tool. A reference sphere can be used instead of a ring bore, with slightly different information elements required. Analysis of results involve computing the range of recorded values [37].
- Information required by probing tool location repeatability test, including ring bore axis line, ring top surface plane, and center point and machine tool coordinate system z-axis line for 10 distinct locations of the probing tool. A reference sphere can be used instead of a ring bore, with slightly different information elements required. Analysis of results involve computing the range of recorded values [37].
- Information required by 2D and 3D probing error tests, including probe points on a ring bore for 2D and reference sphere for 3D used to calculate a world coordinate system. After computations, the analysis produces probing error as a range of measured radial distances, as described in ISO 230-10: 2016 [37].
- Information required by single point time delay variation tests, including time delay variation for individual axes and XY plane circle measurements. After computations, the analysis produces all these results in the X, Y, and Z directions as described in ISO 230-10:2016 [37].

6.1.3 [On-machine, Pre-process] Validate on-machine probes against validated measurement devices at “first part”

6.1.3.1 Use case for validating on-machine probes against validated measurement devices at “first part”

- On a “first part,” prior to the machining and inspection of all other parts of the same type, the system may validate each probe on spindle with an on-machine probing

program on the first part, against validated measurement devices (like temperature-controlled and accurate CMMs).
- If the on-machine probing gives results within a percentage of the tolerance zone measurements from an accurate CMM in an environmentally controlled room – often 10% is used – future parts can be validated with probe on machine. For instance, calibration of an axis to 0.254 mm is not uncommon [3]

6.1.3.2 Information required to validate on-machine probes against validated measurement devices at "first part"

- [Tolerance zones, min_i, max_i[7], for the i^{th} feature, i = 1, 2, … N, for all N features on the part]
- [Tolerance zone measurements from probe on spindle are no more than *x*% less accurate than the same measurements using probes on an accurate CMM]
- [Probe type, probe ID, probe length, probe tip type, probe tip dimensions] for each probe
- [Feature ID, feature type, feature nominal, feature tolerance, feature actual] for each feature
- [CMM name, ID number]
- Assuming the N features on the part are labeled [1, 2, … N], identify [the subset of M features, with M ≤ N, which will be measured on both the CMM and the machine tool]
- [Measurement results for $\mathrm{CriticalFeature}_i$ on first part, i = 1…M] using a more accurate measurement device
- [Probe-on-spindle measurement results for $\mathrm{CriticalFeature}_i$ on first part, i = 1…M]
- [Maximum percentage measurement accuracy of each probe over all M measured features]

6.1.4 [On-machine, Pre-process] Calibrate on-spindle probes using the "reference/artifact comparison" method

6.1.4.1 Use case for on-spindle probe calibration using the "reference/artifact comparison" method

- Calibrate the on-spindle probe against an artifact that has been calibrated at 20°C with uncertainty traceable to a national measurement lab, *e.g.*, the National Institute of Standards and Technology (NIST), the measurement lab for the United States of America, or the National Physical Laboratory (NPL), the measurement lab for the United Kingdom, with these constraints
  - The artifact is the same material as the workpiece
  - The artifact has geometry and features like those on the part
  - Comparative measurement gives traceability, and is independent of machine tool measurement accuracy
  - The artifact is measured using gaging points on the surfaces

[7] Bracketed quantities are the actual information elements

- Thermal effects determined from the artifact measurement are compensated when updating the process variables [3]

6.1.4.2 Information elements required for on-machine probe calibration using the "reference/artifact comparison" method

- Probe [name, type, serial number, length, ball type, ball size]
- Probe calibration results [pass, failed]
- Part material same as artifact [yes/no], part geometry same as artifact [yes/no]
- Lab traceability certification [organization, place, date, serial number]

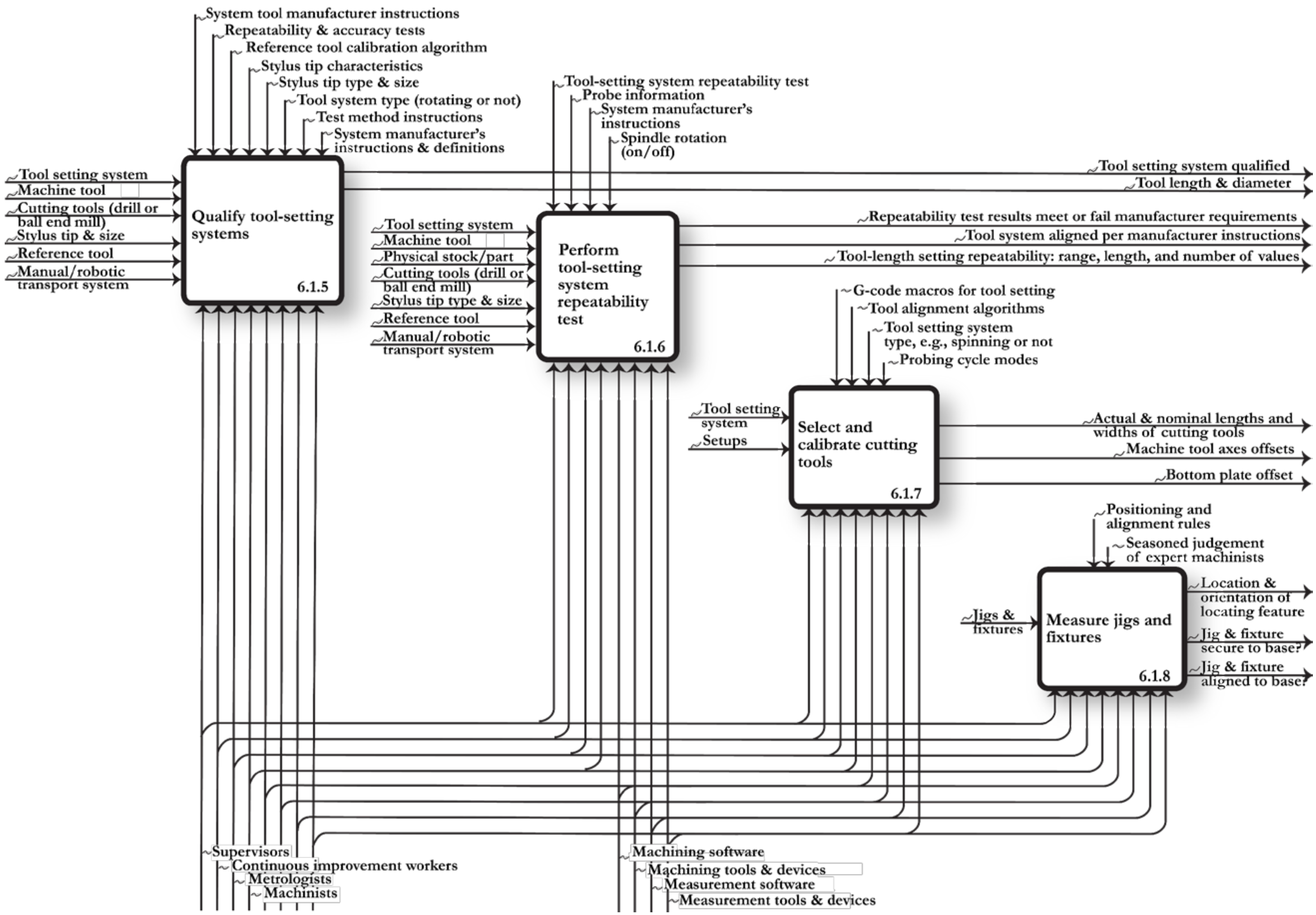

Fig. 5: Measure on-machine pre-process: a subset of activity 6.1 in Fig. 3, illustrating use cases presented below in Section 6.1.5 to Section 6.1.8

6.1.5 [On-machine, Pre-process] Qualify tool setting systems

6.1.5.1 Use case for qualifying tool setting systems

- This use case gives instructions on how to ensure the best performance from a cutting tool setting system (illustrated in Fig. 6), which is a device that measures the length and diameter of a cutting tool for both rotating and non-rotating tools
- The phrase “tool setting system” is sometimes equated with “tool probe system,” “tool probe,” or “sensor system”
- All alignments and operations of the tool setting system must be performed according to the system manufacturer’s instructions
- If a reference tool (or reference artifact) is used to represent the cutting tool, it must be independently calibrated
- More detail is found in ISO 230-10 2016 [37]

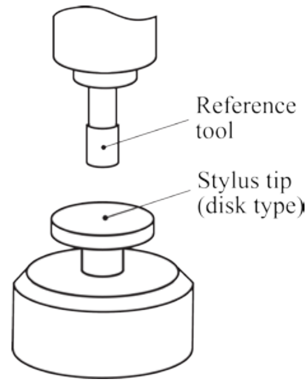

Fig. 6: A tool setting system with reference tool

6.1.5.2 Information elements for qualifying tool setting systems

- Cutting tool system alignment, the operation of tool setting system, and all other activities are set-up and performed strictly according to manufacturer instructions [yes/no]
- Tool system type [rotating, non-rotating]
- Stylus tip type and size [prismatic, cylindrical], which is the device that contacts the tool (or reference artifact) and ends with the stylus tip
- Stylus tip characteristics:
  - Definition: the physical platform (usually) that is touched on the top and side by the reference artifact that substitutes for the cutting tool during calibration
  - Types: [cylindrical, prismatic] (e.g., square)
  - Location within the machine tool coordinate system [x, y, z, i, j, k]
  - Distance to the tool-setting system stylus [d_tool]
  - Distance to the machine tool spindle reference surface [d_spindle]
- Cutting tool or reference artifact: [name, number, diameter, length, calibration history, known location within the machine tool coordinate system]
- “Tool length” is the distance from the bottom of the spindle (or top of the tool holder) to the lowest point on the probe tip [tool length]

6.1.6 [On-machine, Pre-process] Perform tool setting system repeatability test

6.1.6.1 Use case for tool setting system repeatability testing

- Some machine tools have a manual or robotic system to move the tool setting system (illustrated in Fig. 6) into the machine tool workspace. When testing these machines, after each tool measurement, the tool-setting system should be removed and when required, moved again into the machine workspace.

- Performance testing typically requires a unique reference artifact, representing the cutting tool (calibrated for diameter and length) for alignment with the machine tool coordinate system
- Alignment and operation of tool-setting system must be strictly performed according to the system manufacturers instructions
- Both tool length and tool diameter measurements for both rotating and non-rotating tool are in view
- The repeatability test proceeds as follows: measure and record the tool-length ten times using the cycle provided by the manufacturer/supplier. Compute the tool-length setting repeatability as the range of the recorded tool-length values. The spindle must not be rotating during these measurements.
- More detail is found in ISO 230-10 2016 [37]

6.1.6.2 Information elements for tool setting system repeatability testing

- Spindle rotates [yes, no], tool length [l], tool diameter [d], manual probe moving system or robotic probe moving system [manual, robotic]
- Cutting tool type [drill or ball end mill]
- Tool system aligned according to manufacturer instructions [yes/no]
- Tool rotation direction opposite cutting direction [yes/no]
- Repeatability test parameters meet the requirements set by manufacturer/supplier for rotational speed and feed speed [yes/no]
- Tool-length setting repeatability: range [r], length [l], and number of values [n]
- More detail is found in ISO 230-10 2016 [37]

6.1.7 [On-machine, Pre-process] Select and calibrate cutting tools

6.1.7.1 Use case for selecting and calibrating cutting tools

- Determine the size and types of cutting tools required for the part and its features.
- With tool on spindle, measure the length and width of each cutting tool with a tool setting device before cutting begins. Tool setting is sometimes performed while the tool is spinning. Use these measurement values to modify offsets in the MT, to compensate MT axes for actual size of cutting tool. Store the measurement values in the MT, *e.g.*, in G-code or other programming language.
- To perform the above measurements and alignments, several vendors have pre-process alignment systems, with hardware (tool setting devices as in Fig. 6) and software, for tool setting with contact or non-contact measurements. These systems perform the measurement with the tool on spindle, often while the tool is spinning, with both contact probes and non-contact scanners, with software that processes the measured tool length and width to calculate the required offsets for machine tool alignment.
- Probing cycles can be defined or run in either manual or automated mode
- Some tool setting systems come with a touch screen allowing the human operator to enable various inputs and control functions.

6.1.7.2 Information required to select and calibrate cutting tools

- Cutting tool actual size: [length, diameter], nominal size: [length, diameter], and spinning status: [on, off]
- Machine tool axes offsets [(Δx, Δy, Δz) (Δα, Δβ, Δφ)] for [position, roll, pitch, and yaw] gotten from measured cutting tool length and diameter deviations from nominal
- Tool alignment software available: [yes, no], and hardware available: [yes, no]
- G-code macros for tool setting execution
- Probing cycle modes: [manual (*e.g.*, JOG or MDI[8]), automated]
- Cutting tool cycle: [start, stop, reset]
- Setups: [initial, zero tool]
- Bottom plate offset: [plus/minus, offset value]

6.1.8 [On-machine, Pre-process] Measure jigs and fixtures

6.1.8.1 Use case for the measurement of jigs and fixtures toward MT alignment

- Secure the raw workpiece/stock to the machine tool using jigs and fixtures and ensure that it is adequately secured to withstand the unique stresses of the planned machining operations.
- Jigs and/or fixtures – which are designed to position and hold components – might need to be measured while on-machine with some measurement device, *e.g.*, gage, articulated arm CMM, or probe on spindle, at known locations on the jig or fixture, to ensure proper positioning and alignment.
- Depending on the complexity of the machining stock, jigs and fixtures will typically not require any special measurement devices or software other than the seasoned judgement of expert machinists.

6.1.8.2 Information elements required for measurement of jigs and fixtures toward MT alignment

- Actual location and orientation of the locating feature on the fixture in the machine coordinate system, assuming right hand rule for axes: [(x, y, z), (i, j, k)]
- Actual location and orientation of the locating feature on the jig in the machine coordinate system, assuming right hand rule for axes: [(x, y, z), (i, j, k)]
- Fixture/jig in correct alignment: [yes/no]; Fixture/jig secure to MT base: [yes/no]

[8] JOG is motion along an axis at a specified feed rate. MDI, standing for "manual data input," allows manual entry of various codes for direct execution.

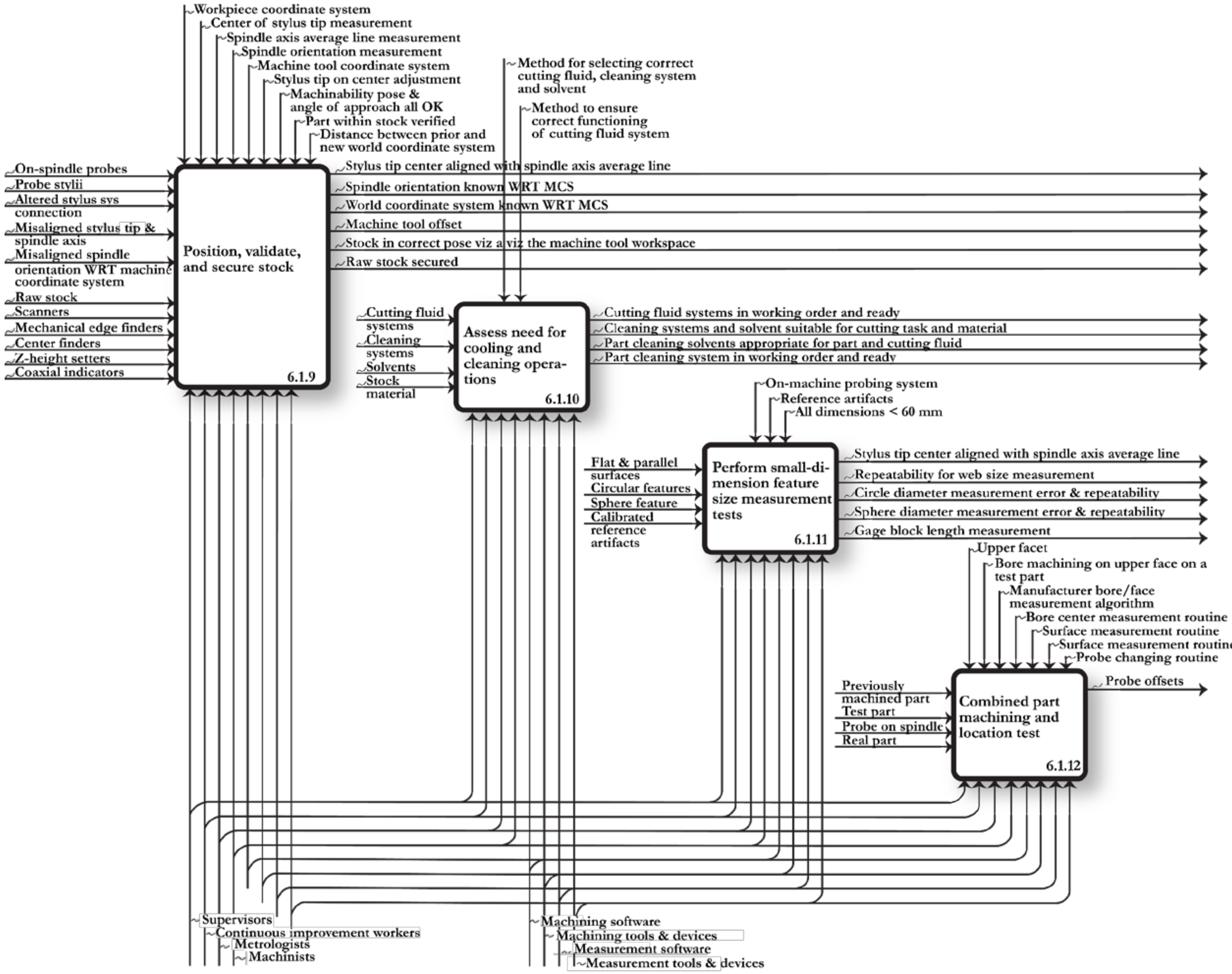

Fig. 7: Measure on-machine pre-process: a subset of activity 6.1 in Fig. 3, illustrating use cases presented below in Section 6.1.9 to Section 6.1.12.

6.1.9.1 Use case for positioning, validating, and securing stock

- This section refers to activity 6.1.9, in Fig. 7.
- Inadequate raw stock alignment can lead to a costly shortage of material. Alignment can also be of high importance, depending on the cost and complexity of the finished part.
- For many probing applications, the center of the stylus tip should be located on the spindle axis average line to allow for proper identification of the workpiece coordinate system (WCS) with respect to the machine coordinate system (MCS).
- In other typical applications, where the alignment of the stylus tip to the spindle axis average line is not of primary concern, care should be taken to ensure that the spindle orientation with respect to the MCS does not change during subsequent probing to avoid the stylus tip offset becoming a significant component of probing error.
- Prior to test execution, stylus tip on-center adjustment shall be performed according to the manufacturer's/supplier's instructions. The adjustment procedure shall be repeated whenever the stylus system connection to the probe is altered. This includes disassembling and re-assembling the same stylus tip as different assembling torques can possibly change the stylus tip center position.
- In many applications, probing on a machine tool is used to reference the raw stock within the machine tool coordinate system and to locate it with respect to the "spindle axis average line." "Workpiece position and orientation tests" are used to perform these measurements. These tests are designed to evaluate this ability of the probing system.
- Positions and orientations of the raw stock mounted on a fixture are sometimes measured with probes, scanners, mechanical edge finders (requiring further offset of a manual dial or digital readout), center finders, z-height setters, and coaxial indicators, and the new coordinate system can then be mapped into the machine tool coordinate system.
- Machinists sometimes employ a software program, computing on measured points, generating an optimal orientation maximizing machining accuracy. This orientation is transferred to the machine tool controller, and the part program can then be run as if the machine tool is perfectly aligned, enabling the machining process to produce features within the desired tolerances. This approach is particularly useful when machining complex free-form parts, when the parts are very large, the parts have varied form or stock, and precise positioning of the part is costly.
- Validate that the stock has the correct dimensions, is in the correct position and orientation in the MT workspace. If not, signal the operator to make appropriate changes in the workspace and/or machining program code.
- Establish a part coordinate system through datum feature location/measurement
- This use case is fully described in ISO 230-10-2016 [37].
- Update the MT offset, as needed, based on the current workpiece location measurement [44]

6.1.9.2 Information required to measure raw stock

- Workpiece/stock secured sufficiently for machinability [yes/no]
- Measured points on raw stock, $[(x_1, y_1, z_1), \dots (x_n, y_n, z_n)]$

- Workpiece/stock position and orientation [(x, y, z), (α, β, γ)] in machine tool coordinate system
- All *n* points, in machine coordinate system, on raw stock are sufficient to discern machinability positions and angles of approach, associated with each position, [machinability positions ((x_1, y_1, z_1), … (x_n, y_n, z_n)) and angles of approach ((α_1, β_1, γ_1), … (α_n, β_n, γ_n))]
- Part is completely imbedded within stock [yes/no]
- New part coordinate system: Position and orientation of part [(x, y, z), (α, β, γ)] within stock in machine coordinate system
- Distances between prior and new part coordinate system: [(Δx, Δy, Δz), (Δα, Δβ, Δγ)]

6.1.10 [On-machine, Pre-process] Assess need for cooling and cleaning operations

6.1.10.1 Use case for assessing need for cooling and cleaning operations

- This section refers to activity 6.1.10, in Fig. 7.
- Ensure that cutting fluid system is in working order and readied for use.
- Ensure that the appropriate cleaning system and solvents for removing cutting fluid and chips prior to measurement are readied for use and in working order.

6.1.10.2 Information required to assess need for cooling and cleaning operations

- Cutting fluid type appropriate for part material and cutting task: [yes/no]
- Cutting fluid system in working order and readied for use: [yes/no]
- Part cleaning solvents appropriate for part and cutting fluid: [yes/no]
- Part cleaning system in working order: [yes/no]

6.1.11 [On-machine, Pre-process] Perform small-dimension feature size measurement tests

6.1.11.1 Use case for performing small-dimension feature size measurement tests

- This section refers to activity 6.1.11, in Fig. 7.
- Measure the distance between two (flat and parallel) surfaces (e.g., webs, slots and steps), the diameter of a circle (e.g., bore and bosses), and the diameter of a sphere for relatively small dimensions (< 60 mm), where a 'web' is something like a pocket. These are measurements commonly available in typical on-machine probing systems.
- In this use case, these measurements are compared against the calibrated size of reference artifacts e.g., gage blocks, deliberately selected to have dimensions smaller than 60 mm in order to test the on-machine probing system performances in a small, limited machine tool volume.
- This comparison provides limited size measurement traceability that should not be extrapolated to assume traceability for size measurement of workpiece features with different sizes. This use case is more fully described in ISO 230-10 2016 [37].

6.1.11.2 Information required to perform small-dimension feature size measurement tests

- The error for web (or pocket) size measurement along the X and Y axes
- The repeatability for web (or pocket) size measurement along the X and Y axes
- The error and repeatability, respectively, for circle diameter measurements

- The error and repeatability, respectively, for sphere diameter measurements
- Gage block length measurements
- These information elements and their uses are more fully described in ISO 230-10 2016 [37].

6.1.12 [On-machine, Pre-process] Test the part machining and location combined

6.1.12.1 Use case for testing combined part machining and location

- This section refers to activity 6.1.12, in Fig. 7.
- A machinist may need to perform additional machining on part features previously machined, requiring that part location (position/orientation) be measured. To enable the accuracy and precision of this operation, a practical on-machine measurement use case has been defined in ISO 230-10-2016 to compare machining to measurement.
- This use case is performed on a test part, prior to additional machining performed on the real part, and involves two operations:
    - Machining a bore and an upper face on a test part
    - Measuring those two features with a probe on-spindle.
- The measured bore center X-axis and Y-axis coordinates should correspond to the programmed bore center coordinates, and the measured upper face Z-axis coordinate should correspond to the programmed Z-axis coordinate.
- The measurement consists of the following steps:
    - Mount the probe on the spindle
    - Measure the bore center using the manufacturer/supplier-recommended measuring routine and record the X- and Y-axis bore center coordinates, X_{BOR} and Y_{BOR}.
    - Measure the faced surface using the measuring routine recommended by the manufacturer/supplier and record the milled surface Z-axis coordinate, Z_{PLA}.
    - Perform a probing-tool change procedure and repeat this testing procedure nine times to acquire a total of ten sets of X_{BOR}, Y_{BOR} and Z_{PLA} measured coordinates
    - Calculate the estimated position and orientation values: [$E_{CML,X}$**,** $E_{CML,Y}$**,** $E_{CML,Z}$**,** $R_{CML,X}$], $R_{CML,Y}$ and $R_{CML,Z}$**(**$E_{\text{Combined Machining and Location, X,Y,Z}}$**), (**$R_{\text{Combined Machining and Location, X,Y,Z}}$**)**
- See ISO 230-10-2016 for a thorough description of this use case.

6.1.12.2 Information required to perform a combined part machining and location test

- $E_{CML,X}$, $E_{CML,Y}$, $E_{CML,Z}$, the combined X-axis, Y-axis, and Z-axis (respectively) machining and location error, gotten from 10 measurements on the test part
- $R_{CML,X}$, $R_{CML,Y}$, $R_{CML,Z}$, the combined X-axis, Y-axis, and Z-axis (respectively) machining and location repeatability, gotten from 10 measurements on the test part

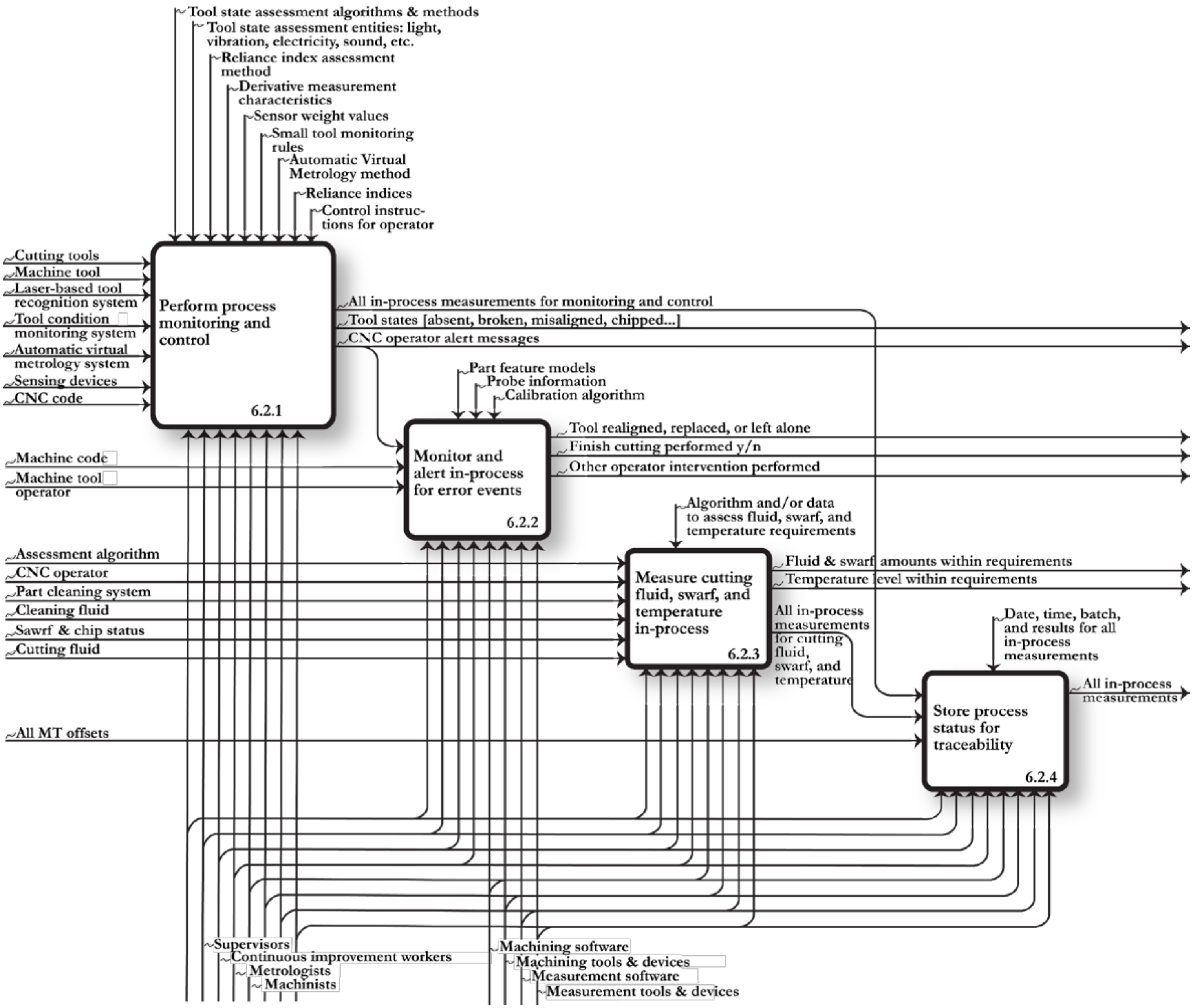

Fig. 8: Measure on-machine in-process: a subset of on-machine measurement activity 6.2 in Fig. 3, illustrating use cases presented below in Section 6.2.1 to Section 6.2.4.

6.2 On-machine in-process measurement use cases

On-machine in-process measurements are described in Table 1 as *measurements performed between the beginning and end of machining, without cessation or pause of cutting operations, where the measurement target is located within the machining workspace and the measurement device is within or nearby the machine tool workspace.*

6.2.1 [On-machine, In-process] Perform process monitoring and control

6.2.1.1 Use case for performing process monitoring and control

- This section refers to activity 6.2.1, in Fig. 8.
- Certain derivative measurements are measured and monitored in-process, with intelligent sensor integration, to estimate important tool characteristics, without interrupting machining operations. These derivative measurement methods have been claimed to produce certain parts faster and cheaper, with sufficient product quality, in comparison to in-process-intermittent measurements, and in spite of the normal turmoil of the machining environment [45-49].
- Measurements (and subsequent operations on those measurements) performed for process monitoring and control are sometimes called virtual metrology or automatic virtual metrology [46] or tool-condition monitoring [47]. These measurements can be gotten using sensing devices – e.g., strain gages [49], tool-condition monitoring systems, electrical current sensors – appropriate for the characteristic being sensed.
- The automatic virtual metrology approach defines a reliance index, consisting of reliability weights for all measurements, intended for sensor integration and more accurate and timely cutting tool state estimates.
- If the machining use case calls for small or delicate cutting tools, more careful and frequent monitoring rules may need to be defined and applied.
- It has been claimed that in-process measurement techniques can perform as well as in-process-intermittent measurement techniques in 20% less time on a wheel machining task [48].
- Tool check systems (sometimes measured by laser light or audio signal monitoring) provides valuable tool status information during the machining process during cutting, by continuously monitoring its dimensions [50], verifying that the tool has been mounted in the spindle, guaranteeing that the performance level remains constant throughout the process, resulting in less rejects and improved machine productivity. These operations are performed automatically on the machine, compiling the measurement data in the tool table. This is possible due to the synergy that exists between the measurement instruments and the software cycles
- Eddy current sensors to detect sub-micron drift of the spindle shaft and communicate the position variation to machine control to initiate axis correction; spindle shaft elongation is due to temperature excursion which can modify the real position of the tools
- Detecting sufficient metal on the part, allowing a finish cutting pass
- With the ability to measure the cutting error in process and adjust the tool offsets with the measure cutting error [2], tool setting may not need to be performed as frequently

6.2.1.2 Information needed to perform process monitoring and control

- Tool states: [tool absent, tool present, tool location, tool pulled-out, tool broken, tool misaligned, tool wear, tool collision, tool excessive vibration, tool chipped, tool sharpness, tool length, tool radius]
- Derivative measurement characteristics: [force, torque, strain, electrical current, acoustic emissions, vibration (chatter), ambient temperature, and local temperature]
- Reliance indices (weighting values) for each sensor measurement indicating the level of uncertainty of that measurement, used to estimate the condition of a cutting tool in-process
- Shape characteristics: [straightness, angularity, perpendicularity, parallelism, roundness]
- Sensing devices: [strain gages, laser-based tool recognition systems, current sensors, force sensors, torque sensors, current sensors, acoustic sensors, vibration sensors, temperature sensors]

6.2.2 [On-machine, In-process] Monitor and alert in-process for error events

6.2.2.1 Use case for monitoring in-process for error events

- This section refers to activity 6.2.2, in Fig. 8.
- Detecting adverse tool states [2], as described in Section 6.2.1, and alerting the operator to perform the appropriate remedy.

6.2.2.2 Information required to realize alert machine tool operator upon error event

- [Operator Alert Message]$_i$: The i^{th} alert message strings for i = 1…N, where N is the number of alert message types, e.g., realign tool, replace tool, leave tool as is, sufficient metal on part for finish cut (y/n), and operator required for assessment and action.

6.2.3 [On-machine, In-process] Measure cutting fluid, swarf, and temperature in-process

6.2.3.1 Use case for the measurement of cutting fluid, swarf, and temperature in-process

- This section refers to activity 6.2.3, in Fig. 8.
- An intelligent process for cleaning tools and workpieces is not trivial and is required for successful machining, inspection, and final finish [44, 51]. The presence of chips (swarf) and/or cutting fluid on a part during a dimensional measurement can lead to rejecting a good part or accepting a bad one. Measuring (or detecting) cutting fluid, swarf, and temperature in-process, if performed intelligently, can save time and improve part quality.
- In-process cleaning is commonly performed with sprayers to mitigate chips and cutting fluid remaining on the part, but the authors of this research know of no measurement of cutting fluid performed *in-process*, though it certainly could and perhaps should be done, if only to have real-time assurance that the cutting fluid contents and application are sufficient.

- Certain sensing systems perform in-process detection of tangles of swarf on the cutting tool [52].
- The temperature of the part or the ambient temperature in the machine tool workspace can be measured in-process. If the temperature rises too high, actions can be taken in-process to lower part temperature.
- There must be some measurement/assessment of the presence or absence of cutting fluid during machining operations, since cutting fluid can be so critical to high-speed cutting of many materials.

6.2.3.2 Information required for the measurement cutting fluid, swarf, and temperature in-process

- Cleaning fluid [name, type]
- Cutting fluid [name, type, status]
- Swarf/chip [status (e.g., attached to cutting tool)]
- Cleaning (sprayer) system [name, manufacturer, ID number]
- Temperature [ambient, tool, part, cutting fluid]

6.2.4 [On machine, In-process] Store process status for traceability

6.2.4.1 Use case for storing process status for traceability

- This section refers to activity 6.2.4, in Fig. 8.
- Store in-process measurements and offset updates for subsequent traceability, to perform a post mortem on past machining operations, to avoid such problems in future operations.

6.2.4.2 Information required to store process status for traceability

- All in-process measurements, with full associativity to date, time, batch, measurement results, and any other relevant information

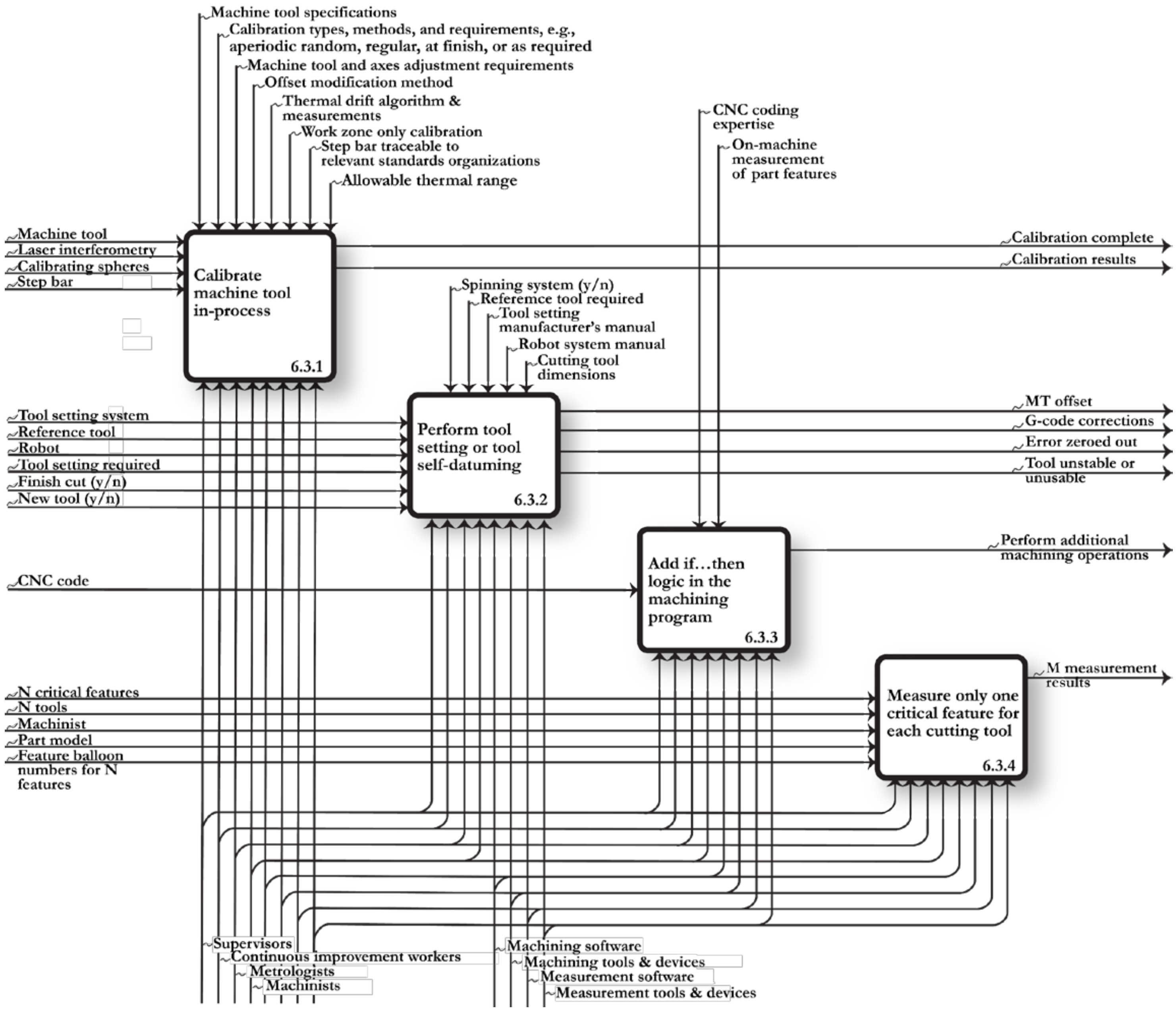

Fig. 9: On-machine in-process-intermittent use cases: a subset of on-machine measurement activity 6.3 in Fig. 3, illustrating use cases presented below in Section 6.3.1 to Section 6.3.4

6.3 On-machine in-process-intermittent measurement use cases

On-machine and in-process-intermittent measurements are described in Table 1 as *measurements performed after cutting begins, before the part is removed from the machine tool fixture, during a cessation of cutting operations, where the measurement target is located within the machining workspace and the measurement device is within or nearby the machine tool workspace.*

6.3.1 [On-machine, In-process-intermittent] Calibrate machine tool in-process

6.3.1.1 Use case for calibrating machine tool in-process

- This section refers to activity 6.3.1, in Fig. 9.
- In-process measurement results can drive the need to calibrate, adjust axes, modify offsets, repair axes, or move to a different machine tool in-process.
- Machine tool and tool axes are calibrated a-periodically, regularly, and/or when required, especially when thermal drift is detected or before finishing operations.
- Laser interferometry, calibrating spheres, and other technologies are used for tool and tool axes calibration.
- Use appropriate calibration measurement methods specified in the "Calibration MT prior to operation on stock or on part, leading to MT alignment," in Section 6.1.1.
- Work zone only calibration saves time and can be just as effective.
- After calibration, machine accuracy is measured with a "step bar" that is traceable to national metrology institutes, *e.g.*, NIST [3].
- Adjust MT axes and/or update MT offsets as required by the calibration results.

6.3.1.2 Information required to calibrate machine tool in-process

- Machine tool axes drift algorithm requiring recalibration: [yes/no]
- Allowable thermal range: [Temp_{low}, $\text{Temp}_{\text{high}}$]
- Calibration accomplished: [yes/no]
- Machine tool calibration types: [aperiodic random, regular, at finish, or as required]
  - If aperiodic, use random number generator with average time, T_{avg}, and standard deviation, σ
  - If regular, always calibrate after time, T, of machining operations
  - If at finish, calibrate when machining is complete
  - If as required, calibrate when calibration is required
- Calibration types: [laser interferometer system, calibrating sphere system, etc. as available]
- Calibrate work zone only: [yes/no]
- Traceably accurate step bar calibration required: [yes/no]
- Machine tool axes/offsets adjustments: [[Δx, Δy, Δz], [Δα, Δβ, Δγ]]

6.3.2 [On-machine, In-process-intermittent] Perform tool setting or tool self-datuming

6.3.2.1 Use case for performing tool setting or tool self-datuming

- This section refers to activity 6.3.2, in Fig. 9.

- Use tool setting device, also known as tool self-datuming device, to measure the size of cutting tools during cutting operations. One such system automatically computes the machine tool offset and makes the correction in the G-code. This is called "zeroing-out" the error in the cutting tool probe. The tool measurement is commonly performed while the tool bit is spinning. The bit is measured from the bottom and from both sides. It can also detect a broken tool.
- May need to perform tool self-datuming just prior to the finish cut, since accurate tool location is even more important.
- Some tool setting systems involve a robot to move the tool to the tool setting device
- Manufacturers also do tool setting on roughing tools as well as on finishing tools, since a feature with an uncertain rough cut can cause a number of error producing problems, including tool deflection and poor surface finish [2].

6.3.2.2 Information required to perform tool setting or tool self-datuming

- Tool setting required = [yes/no]; Information elements: Cutting tool size = [tool length, tool width]; Machine tool axes/offsets adjustments: [[Δx, Δy, Δz], [$\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$]]; Cutting tool state = [usable or unusable]; finish cut = [yes/no].
- New tool = [yes/no].

6.3.3 [On-machine, In-process-intermittent] Add if…then logic in the machining program

6.3.3.1 Use case for adding if…then logic in the machining program

- This section refers to activity 6.3.3, in Fig. 9.
- Define and incorporate if…then logic (*e.g.*, if $measurementResult_i$, then machining $code_i$) into the machining code to perform different operations depending on measurement results, perhaps requiring another finishing pass. [2]

6.3.3.2 Information required to add if…then logic in the machining program

- [$measurementResult_i$, machining $code_i$] for i = 1…N

6.3.4 [On-machine, In-process-intermittent] Measure only one critical feature for each cutting tool

6.3.4.1 Use case for measuring only one critical feature in a set of features created by one cutting tool

- This section refers to activity 6.3.4, in Fig. 9.
- Rather than measure every feature cut by the same tool, depending on other factors, an efficient option might be to measure only one feature in the set of features created by the same cutting tool for each pass [2].
- These types of measurement are typically performed on precision CNC CMMs.

6.3.4.2 Information required to measure only one critical feature in a set of features created by one cutting tool

- $cuttingTool_i$ = [$cuttingToolName_i$, $cuttingToolNumber_i$] for i = 1…M, where M is the number of cutting tools used to machine the part
- $featureSet_i$ = i^{th} set of features on the part, where the sets are nonintersecting but cover the whole set of features, and all features in the set

- featureNumber = “balloon” number for the critical feature
- $criticalFeature_i$ = the most important feature in $featureSet_i$
- $measurementResults_i$ = measurement of $criticalFeature_i$

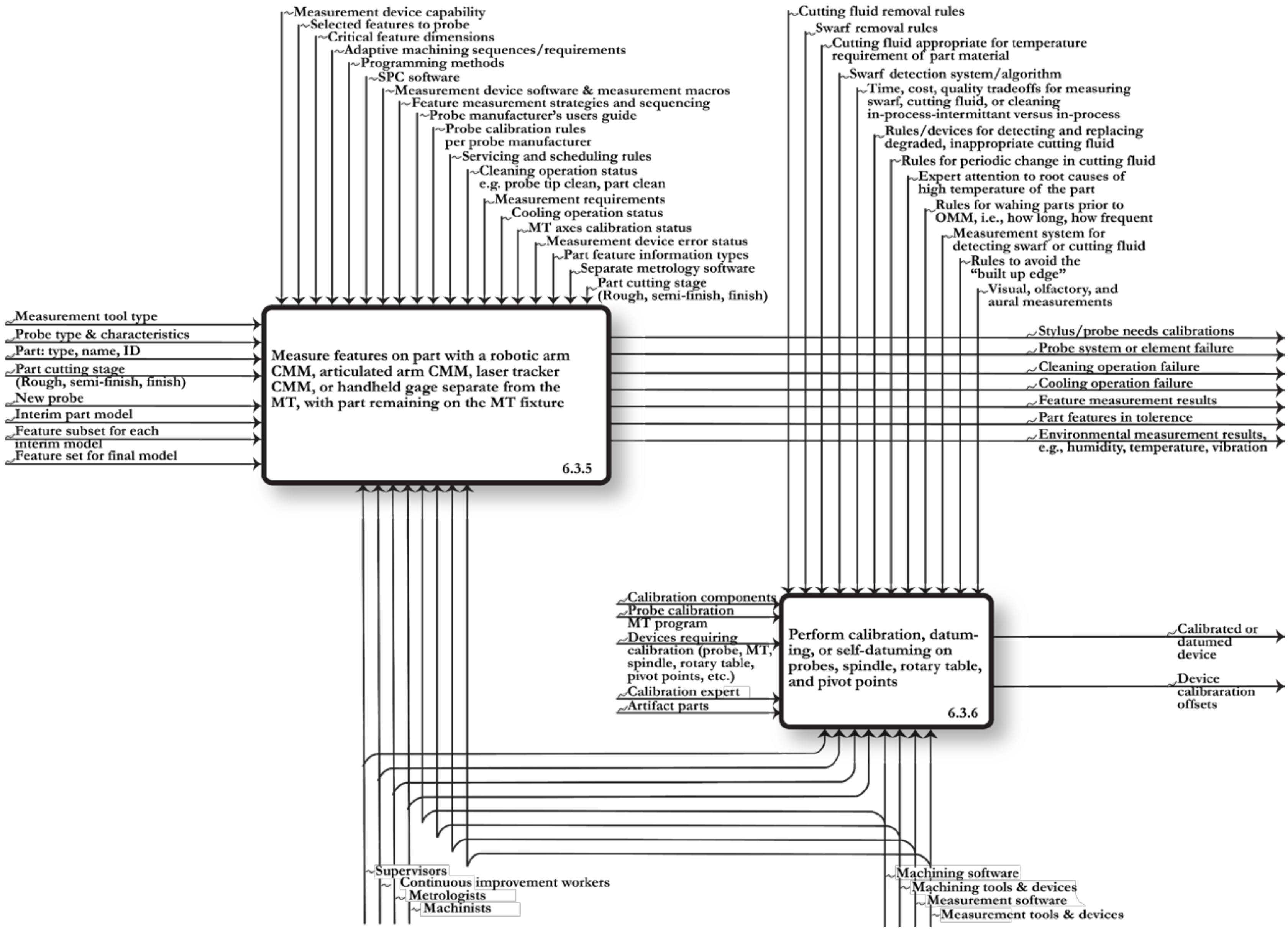

Fig. 10: On-machine in-process-intermittent use cases: a subset of on-machine measurement activity 6.3 in Fig. 3, illustrating use cases presented below in Section 6.3.5 to Section 6.3.6.

6.3.5 [On-machine, In-process-intermittent] Measure features on part with part remaining in the MT workspace, but with a robotic arm, articulated arm CMM, laser tracker CMM, or handheld gage separate from the MT

6.3.5.1 Use case for measure features on part with part in the MT workspace, but with measurement devices separate from the MT

- This section refers to activity 6.3.5, in Fig. 10.
- A part must be within the machine tool's workspace, using a precision robot, an articulated arm CMM, or a laser tracker CMM for feature probing.
- This use case is non-trivially similar to the use case described in Section 6.3.7 and shown in Fig. 11, except that the measurement device is not probe on MT spindle.

6.3.5.2 Information required for measure features on part with measurement devices separate from the MT, with part remaining on the MT fixture

- Measurement device characteristics:
  - Robotic arm
  - Laser tracker CMM
  - An articulated arm CMM, with touch probe and/or non-contact scanner, would either be mounted on the machine tool bed within the machining workspace or just outside the machining workspace, and may be calibrated with respect to the machine tool and part axes.
  - A handheld gage operated manually measuring features on the part without removing the part from the spindle.
  - Measurement device performance values, e.g., [probe speed, probe accuracy]
- Interim part model number [i = 1...n], includes the finished model
- Subset of all features required to measure on the i^{th} interim part [i = 1...n] (see feature types listed below)
- Subset of all features required to be measured on the finished part (see feature types listed in the Appendix), often called "ballooned" features, with feature numbers assigned to each of m measured features $[\text{feature\_name, feature\_number}]_j$ [j= 1...m]
- Measurement strategies
  - Probe speed of approach for measurement [maximum speed, safe speed]
  - Manual or automatic with software
- Stock bounding region
- Part and feature characteristics
- Measurement requirements
- Servicing and scheduling rules
- Cleaning operations status
  - Probe tip clean, yes/no
  - Optical device clean, yes/no
  - Part surface clean, yes/no
- Cooling operations status
- Probe characteristics
  - Probe type [touch [kinematic resistive or strain gage], non-contact optical, non-contact laser, 2D, or 3D]
  - Length of shank plus ball

  - Ball type *e.g.*, spherical, elliptical
  - Ball radius/width
  - Calibration status [probe axis offsets [Δx, Δy, Δz], time since last calibration]
  - Probe approach speeds for measurement [maximum, safe]
  - Probe accuracy at [maximum, average, slow] approach speeds
- Measurement equipment error status
- Measure in-process command
- Physical stock/part name and number
- Measurement equipment program format, *e.g.*, proprietary, standard
- Feature measurement sequencing rules
- Feature measurement sequence
- Part feature information types (see Appendix)

6.3.6 [On-machine, In-process-intermittent] Perform calibration, datuming, or self-datuming on probes, spindle, rotary table, and pivot points

6.3.6.1 Use case for performing calibration, datuming, or self-datuming on probes, spindle, rotary table, and pivot points

- This section refers to activity 6.3.6, in Fig. 10.
- Check for mechanical, environmental, and electrical errors in the probe on MT spindle and, if they exceed maximums, perform calibration
- Perform calibration using (typically) calibration components and a probe calibration machine tool program with whatever additional human involvement is required
- Calibration components include artifacts, probe, spindle, rotary table, pivot points, machine tool, ring gages, setting gages of known length, probe setting device, interferometers, dial test indicators, probe setting devices, and/or calibration spheres
- Calibration routines are too numerous and variable to catalog, so follow the device manufacturer's calibration instructions
- Probe calibration is called "zeroing-out" the error in the probe on the MT spindle, implying that any position/size changes in the probe are compensated for in the machining software. These routines may be automated, but may need to be repeated in-process-intermittent on an "as-needed" basis [3].
- If probe self-datuming is required, calibrate the probe against an already calibrated probe to ensure that required accuracies are achieved across all probes throughout the on-machine measuring process.
- Calibration is typically done at regular intervals [3], though if a probe is swapped out for a different sized probe, if the part is high-valued, if some probe anomalies indicate need for checking the probe, including if the probe was dropped or hit, if the stylus assembly is loose, if the stylus assembly is out of square, or if the probe is scheduled for self-datuming, perform a probe calibration.
- Datum the probe(s) off artifact parts before performing final inspection probing, if required ("artifact parts" are parts of precisely known dimension, like ring gages or gage blocks).

6.3.6.2 Information required to perform calibration, datuming, or self-datuming on probes, spindle, rotary table, and pivot points

- Events and conditions requiring calibration = [time interval, new probe, probe is swapped out for a different sized probe, high-value part, probe anomalies indicate need for checking the probe (including if the probe was dropped or hit), the stylus assembly is loose, suspected or known mechanical probe errors, environmental changes exceeding some maximum, electrical probe errors exceeding some maximum, scheduled probe calibration required]
- Probe calibration offset results: on axis offsets [Δx, Δy, Δz] and discrete angular offsets $[\Delta x, \Delta y]_{\theta}$, $\Theta \epsilon (0, 2\pi)$
- Calibration machine tool programs with any instructions for execution

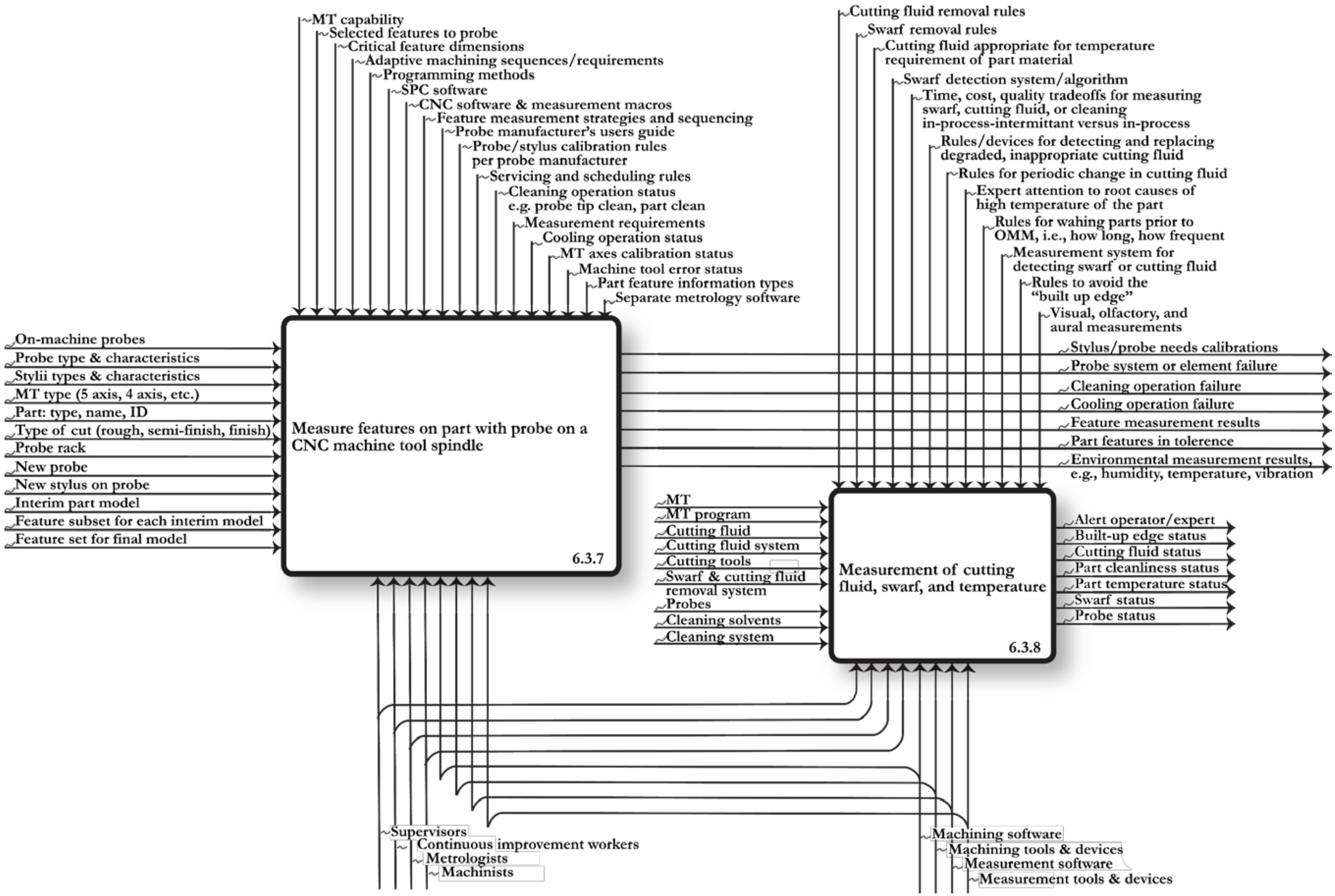

Fig. 11: On-machine in-process-intermittent use cases: a subset of on-machine measurement activity 6.3 in Fig. 3,, illustrating use cases presented below in Section 6.3.7 to Section 6.3.8.

6.3.7 [On-machine, In-process-intermittent] Measure features on part with probe on a CNC machine tool spindle

6.3.7.1 Use case for measuring features on part with probe on a CNC machine tool spindle

- This section refers to activity 6.3.7, in Fig. 11.
- Probing on-machine in-process intermittent with probe on spindle is perhaps the most common and visible on-machine measurement use case. It is a very rich use case, and the following description omits a significant depth of detail.
- Measure all or only selected features on a part located within the machine tool workspace with a probe on the machine tool's spindle. The probe system performs and is designed much like probe systems found on CMMs.
- The measurement is directed by measurement code in CNC manufacturer's software or in a separate software system, integrated with the machine tool and uniquely designed for on-machine measurement with a probe on spindle.
- Multiple probes of different sizes may be used, requiring the swapping of probes, either manually or using a probe rack.
- Probes may need to be calibrated, before they are put into use, for any of the following reasons [53]. See Section 6.1.2 for a detailed description of probe calibration.
    - A probe system is put into use for the first time
    - A new stylus is fitted to the probe
    - When it is suspected that the stylus has become distorted or that the probe has crashed
    - At regular intervals to compensate for mechanical changes of the machine tool
    - When repeatability of relocation of the probe shank is poor, in which case, the probe may need to be recalibrated each time it is selected
- On-machine probes are used in the context of certain machining use cases, such as "adaptive machining," sometimes called, "creeping up" [54]. In this machining use case, measurements are performed after preliminary cutting on the selected feature, which can lead to either scrapping the part or (more commonly) modifying machine tool offsets; a couple of examples of probe on spindle operations in the adaptive machining use case are "cut/measure/final cut" or "cut/measure/finish cut/measure/final cut." These operations involve particularly targeting critical feature types and/or expensive stock material. The following operations describe adaptive machining and how in-process measurement is involved.
    - Cut the part to some shape, which may be either an interim part an interim part close to finished size, or an unplanned interim part, requiring an unscheduled need to measure, *e.g.*, a broken tool bit
    - Probe the semi-finish cut, with a probe on the machine tool spindle
    - Adjust the machine offsets for any part deflections, tool deflections, tool wear, and other factors
    - After adjusting the machine offsets, bring the part into tolerance with a final cut.

- The probes are datumed off reference artifacts e.g., gage blocks, before performing final inspection probing.
- The inspection data may be used to accept or reject the part and may be recorded for Statistical Process Control (SPC) analysis

- Programming methods
  - Perform programming probe manufacturer's software, either in direct or batch mode, where the batch mode allows more powerful measurement capabilities, but with slower measurement execution throughput. Some on-machine inspection solution providers also provide software that will generate the entire measurement program and execute from the inspection software company's software. This allows more sophisticated measurement processes, but the program runs a little slower than inspection software routines run from the machine tool.
  - G-code macros have been written to direct a machine tool to measure any point, but the machine tool programmer must create the G-code program to accomplish the measurement.
- May measure environmental characteristics, such as, (ambient and part) temperature and humidity in the in-process environment

6.3.7.2 Information required to measure features on part with probe on the machine tool spindle

- Machine tool characteristics:
  - Machine type, *e.g.*, 6-axis, 5-axis, 4-axis, 3-axis
  - Machine tool performance values [probe speed, probe accuracy]
- Interim part model number [i = 1...n], includes the finished model
- Subset of all features required to measure on the i^{th} interim part [i = 1...n] (see feature types listed below)
- Subset of all features required to be measured on the finished part (see feature types listed in the Appendix), often called "ballooned" features, with feature numbers assigned to each of m measured features [feature_name, feature_number]$_j$ [j= 1...m]
- Measurement strategies
  - Probe speed of approach for measurement [maximum speed, safe speed]
  - Program with G-code measurement modules, or use external software
- Stock bounding region
- Part and feature characteristics
- Measurement requirements
- Servicing and scheduling rules
- Cleaning operations status
  - Probe tip clean, yes/no
  - Part surface clean, yes/no
- Cooling operations status
- MT axes calibration status
- Probe characteristics
  - Probe type [touch [kinematic resistive or strain gage], non-contact optical, non-contact laser, 2D, or 3D]
  - Length of shank plus ball

- Ball type *e.g.*, spherical, elliptical
- Ball radius/width
- Calibration status [probe axis offsets [Δx, Δy, Δz], time since last calibration]
- Probe approach speeds for measurement [maximum, safe]
- Probe accuracy at [maximum, average, slow] approach speeds

- Machine tool error status
- Measure in-process command
- Physical stock/part name and number
- Machine tool program format, *e.g.*, G-code program, proprietary, STEPNC
- Feature measurement sequencing rules
- Feature measurement sequence
- Part feature information types (see Appendix)

6.3.8 [On-machine, In-process-intermittent] Measure cutting fluid, swarf, temperature, and part cleaning, performed with cessation of cutting operations

6.3.8.1 Use case for measuring cutting fluid, swarf, temperature, and part cleaning, performed with cessation of cutting operations

- This section refers to activity 6.3.8, in Fig. 11.
- An intelligent process for applying and measuring the quality of cutting fluid at appropriate times in the cutting process, and an intelligent process for cleaning tools, probes, and workpieces at appropriate times in the on-machine measurement process, are both required for successful machining, inspection, and final finish. [44, 51].
- Applying cutting fluid to both the part and the cutting tool for cooling, and applying cleaning fluid to the part and cutting tool to remove cutting fluid and swarf, are based on
  - machine tool operator experience
  - instructions from system vendor manuals
  - visual, olfactory, and aural measurements
- The use of poor, degraded, insufficient, or inappropriate cutting fluid can cause unstable temperature variance on the part and tool. It is expected that status of the cutting fluid will be measured, or the cutting fluid will be changed at intervals, given the potentially serious consequences of unsuitable cutting fluid. It is expected that a simple periodic change of cutting fluid will be sufficient for many machining operations, though machinists should consult with cutting fluid usage instructions, based on the machine tool type, the part material type, and productivity requirements, e.g., feeds and speeds.
- Cutting fluids are necessary for cutting tools but can be damaging to measurement probes. Not washing prior to measuring with a probe can lead to probing on swarf and/or cutting fluid, leading to rejecting a good part or accepting a bad one. Cutting fluids are designed to adhere to surfaces to sufficiently lubricate the cutting edge and to prevent the red-hot chips from welding to the cutting tool. However, successful on-machine part measurement depends on the removal of any adhering cutting fluid.

Even if the part is air-blown, residual lubricant film is a problem, as fluid film can transfer to the probe, which can collect floating dust and debris. There must be a washing system with solvents to remove film and debris from the part, prior to probing. Cleaning cutting fluid and swarf off parts in-process-intermittent takes time from both the measuring and the machining processes, so there are time, cost, and quality trade-offs to consider when deciding whether and when to wash off parts and tools, for a given machining operation.

- Successful cleaning processes are dependent on a variety of metalworking fluids and cleaning devices, including manual, mechanical, robotic, and other automatic techniques. Liquid sprayers (washing systems) and magnetic tools are used for swarf removal. Washing systems manufacturers should have guidelines for effective use.
- Without a cleaning cycle with solvents, along with choosing the appropriate tool speed and lubricant, a “built-up edge” can happen, which is an accumulation of material against the cutting front of the tool that seizes to the tool tip, separating it from the chip. This can be very detrimental to the part, the tool, and even the machining center, causing vibration and drag [55]. The authors are not aware of any automated and quantitative measurement used to detect the built-up edge.
- Cleaning takes time from both the measuring and the machining processes, so there are time, cost, and quality trade-offs to consider when deciding whether to measure on-machine in-process for a given operation. Some probes on machine tool spindles are equipped with sprayers (*e.g.*, air) to mitigate chips and cutting fluid remaining on the part.
- To remove undesirable materials from parts or components, parts cleaning equipment is sometimes used for the processes of metal cleaning, metal surface cleaning, component cleaning and degreasing.
- Temperature variance is often taken care of by the cutting fluid spray that is normally active during all contact between the spinning tool and the part. However, if part temperature is too elevated, in-process probing may need to be delayed until part temperature is sufficiently low.

6.3.8.2 Information required for removing chips and liquid from the work piece during machining, and stabilizing temperature variance

- Machine tool [manufacturer, model number, type, date, calibration status]
- Machine tool program [author, version, date]
- Cleaning solvent [type, manufacturer/provider, condition]
- Cleaning system [name, manufacturer, ID number, status]
- Cutting fluid [type, manufacturer/provider, condition]
- Cutting fluid system [manufacturer/provider, ID number, status]
- Swarf/cutting fluid removal system [ready to measure, not ready to measure]
- Swarf/chip status [ready to measure, not ready to measure]
- Temperature status [ready to measure, not ready to measure]
- Probe [manufacturer, type, dimensions, calibration status]

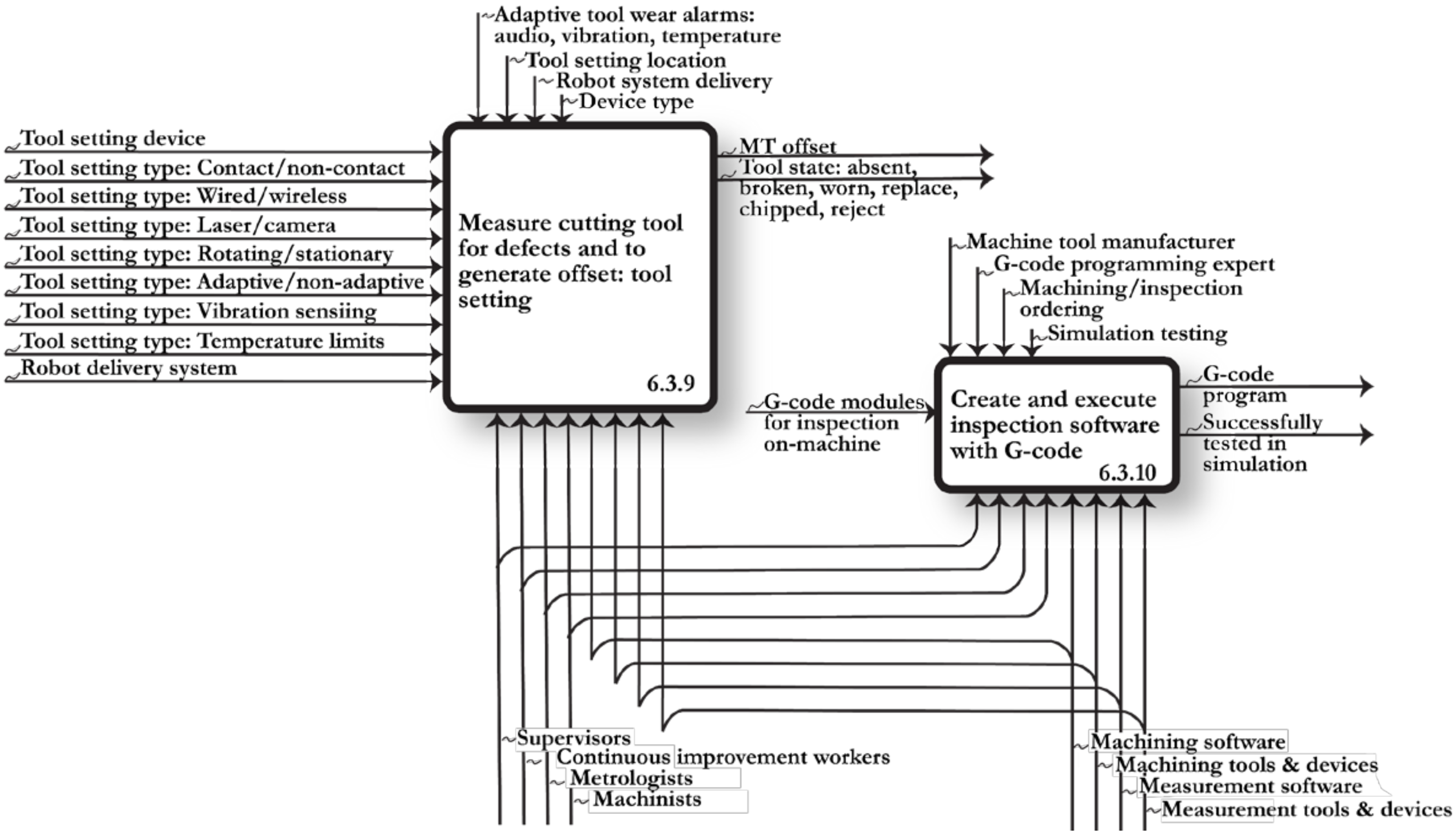

Fig. 12: On-machine in-process-intermittent use cases: a subset of activity 6.3 in Fig. 3, illustrating use cases presented below in Section 6.3.9 to Section 6.3.10.

6.3.9 [On-machine, In-process-intermittent] Measure cutting tool in-process-intermittent for defects and to generate offsets

6.3.9.1 Use case for measuring cutting tool in-process-intermittent for defects and to generate offsets

- This section refers to activity 6.3.9, in Fig. 12.
- Tool setting device activities, see an example in Fig. 12, can be parsed into in-process (described in Section 6.2.1), in-process-intermittent, contact/non-contact, length & width measurement, wired/wireless, laser/camera [43], rotating/stationary tool, adaptive/non-adaptive tool wear capability, temperature limits, vibration sensing for detecting or preventing breakage (acoustic emission [35] or coolant flow monitoring).
- Tool setting device is mounted in the machine tool workspace for tool condition measurements. May require a robotic system to move the cutting tool to the tool setting device
- MT offsets are updated after measurement of length and width
- System rejects cutting tool if deemed defective

6.3.9.2 Information required for tool setting

- Tool setting system type [contact/non-contact, wired/wireless, laser/camera, rotating/stationary tool, adaptive/non-adaptive, single system or collection of devices, acoustic, coolant flow sensing]
- Tool status [no adjustments required, MT offset required]
- MT tool offsets: changes in position [Δx, Δy, Δz], and changes in roll, pitch, and yaw [$\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$], based on cutting tool actual size

6.3.10 [On-machine, In-process-intermittent] Create and execute inspection software in-line with G-code

6.3.10.1 Use case for creating and running inspection software in-line with G-code

- This section refers to activity 6.3.10, in Fig. 12.
- On-machine metrology activities are embedded in machining (NC code) controller, and executed along with machining operations, allowing communication from former to latter

6.3.10.2 Information required to create and execute inspection software in-line with G-code

- Each inspection module activity represented in G-code
- A natural language description of each inspection module activity

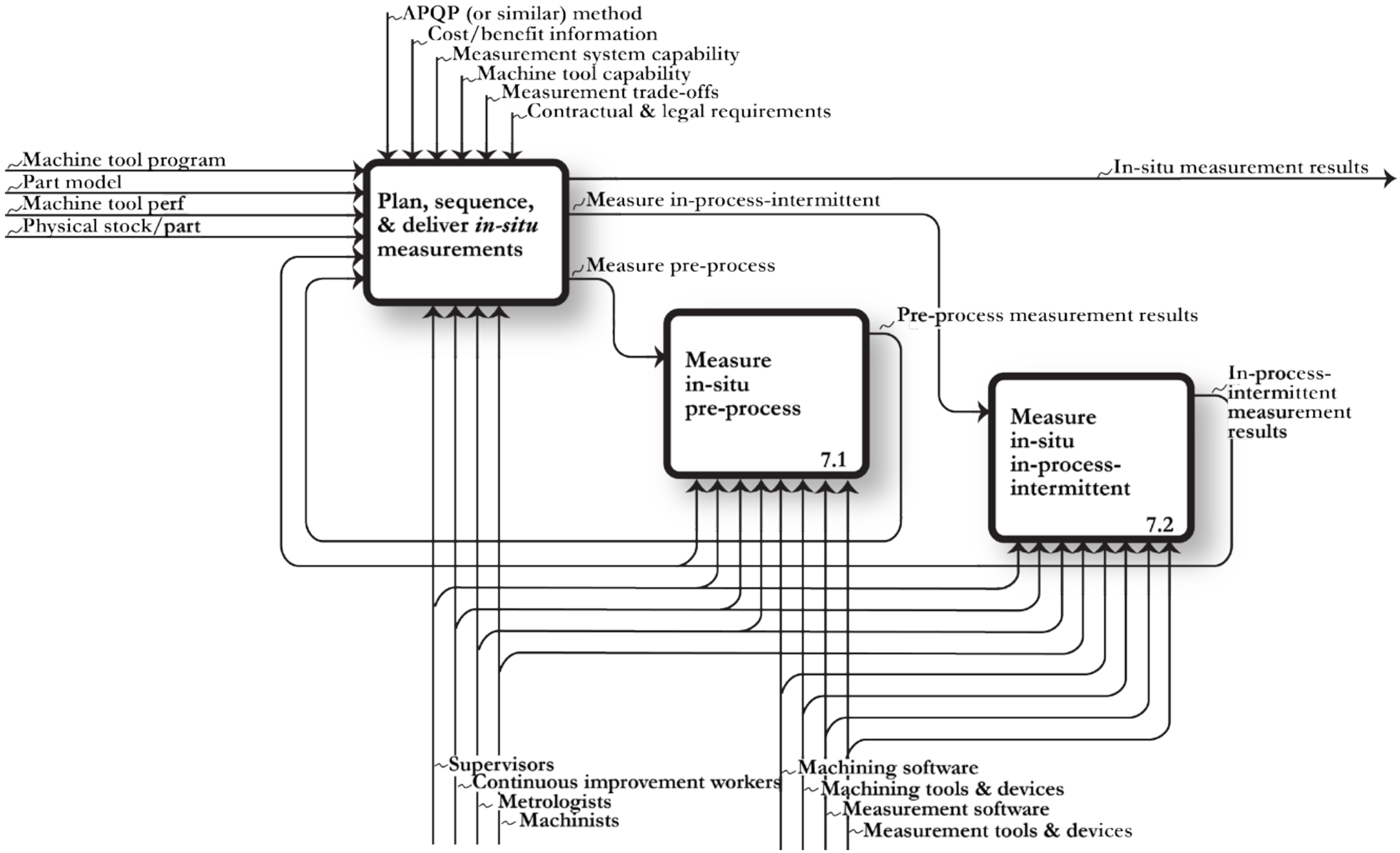

Fig. 13**:** Plan and perform in-situ measurements: a subset of activity 7 in Fig. 2, described in Sections 7.1 and 7.2.

7 In-situ use cases and information elements

In this section and the next, we present a pair of measurement categories, namely, in-situ and off-machine, which are both related to on-machine measurement. This is consistent with our research goal to provide a broad set of syntactical and semantic information useful to relevant manufacturing information exchange standards organizations.

7.1 In-situ pre-process use cases

In-situ pre-process measurements are measurements performed before cutting begins where the measurement target and measurement device are located outside, but nearby, the machine tool workspace, irrespective of whether the measurement target is mapped to the machine tool coordinate system. This type of measurement is outside the scope of this research.

7.2 In-situ in-process-intermittent use cases

In-situ in-process-intermittent measurements are described in Table 1 as *a measurement performed after cutting begins, before the part is removed from the machine tool fixture, during a cessation of cutting operations, where the measurement target and measurement device are located outside, but nearby, the machine tool workspace, irrespective of whether the measurement target is mapped to the machine tool coordinate system.*

7.2.1 [In-situ, in-process-intermittent] Measure a part, outside the machine tool workspace, but nearby the machine tool with a measurement device calibrated to the machine tool reference frame

7.2.1.1 Use case for measuring a part, outside the machine tool workspace, but nearby the machine tool with a measurement device calibrated to the machine tool reference frame

- In this use case, the stock/part is moved from the CNC machine to a separate measurement device to a location outside the machine tool workspace, but at precise, known, and calibrated location within the machine tool reference frame. After the measurement, the part can be brought back to the machine tool for further machining.
- The measurement device may be a fully equipped automated programmable Coordinate Measuring Machine (CMM), with the part affixed to a flexible fixture system, sometimes called an “in cell” or “tombstone” CMM [18, 56], which can be moved, *e.g.,* rotated, to present the part to either the machine tool or the CMM.
- In this use case, swapping in/out probes on the machine tool spindle is not required.
- Because the part is physically outside the workspace of the MT and the probe is on a CMM, this use case cannot be considered an on-machine measurement according to the definitions in Section 3.
- With the part on the tombstone fixture, washing and cooling the part in the machine tool workspace prior to measurement may be required.
- Calibration measurements of the tombstone itself will be required periodically.

7.2.1.2 Information elements to measure the part, outside the machine tool workspace, but nearby the machine tool with a measurement device calibrated to the machine tool reference frame

- Interim part model number [i = 1...n], includes the finished model
- Subset of all features required to measure on the i^{th} interim part [i = 1...n] (see feature types listed in the Appendix)
- Subset of all features required to be measured on the finished part (see feature types listed in the Appendix), often called "ballooned" features, with feature numbers assigned to each of *m* measured features $[\text{feature\_name}, \text{feature\_number}]_j$ [j= 1...m]
- Measurement strategy for probe speed of approach for measurement [maximum speed, safe speed]
- Stock bounding regions for interim part models
- Part and feature characteristics
- Measurement requirements
- Measurement strategies
- Servicing and scheduling rules
- Cleaning operations status
  - Probe tip clean, yes/no
  - Part surface clean, yes/no
- Cooling operations status
- Measurement device axes calibration status
- Probe characteristics
  - Probe type [touch (kinematic resistive or strain gage), non-contact optical, non-contact laser, 2D, or 3D]
  - Length of shank plus ball
  - Ball type *e.g.*, spherical, elliptical
  - Ball radius/width
  - Calibration status [probe axis offsets [Δx, Δy, Δz], time since last calibration]
  - Probe approach speeds for measurement [maximum, safe]
  - Probe accuracy at [maximum, average, slow] approach speeds
- Measurement device errors status
- Measure [in-situ, in-process-intermittent] command
- Physical stock/part name and number
- Measurement equipment program format
- Feature measurement sequencing rules
- Feature measurement sequence
- Part feature information types [57] (see Appendix)

7.2.2 [In-situ, In-process-intermittent] Measure a part outside the machine tool workspace, but nearby the machine tool with a measurement device not calibrated to the machine tool reference frame

7.2.2.1 Use case for measuring a part outside the machine tool workspace, but nearby the machine tool with a measurement device not calibrated to the machine tool reference frame

- During a cessation of the on-machine machining operation, move the part out of the machine tool workspace to a location nearby the machine tool workspace to perform measurements on some aspect of the part, but not in a temperature-controlled CMM room
- A separate measuring device, *e.g.*, robotic CMM, located nearby the machine tool workspace, will be used to measure certain features on the part
- The part on the measuring device will be in a coordinate system that is not mapped to the machine tool axes
- When measurement operations are done, the part may or may not be returned to the machine tool fixture for more machining operations, based on the results of the measurements

7.2.2.2 Information required to perform a measurement, outside the machine tool workspace, but nearby the machine tool

- Interim part model number [i = 1...n], includes the finished model
- Subset of all features required to measure on the i^{th} interim part [i = 1...n] (see feature types listed in the Appendix)
- Subset of all features required to be measured on the finished part (see feature types listed in the Appendix), often called "ballooned" features, with feature numbers assigned to each of m measured features $[\text{feature\_name, feature\_number}]_j$ [j= 1...m]
- Measurement strategy for probe speed of approach for measurement [maximum speed, safe speed], would not be necessary for articulated arm and laser tracker CMMs
- Stock bounding regions for interim part models
- Part and feature characteristics
- Measurement requirements
- Measurement strategies
- Servicing and scheduling rules
- Cleaning operations status
    - Probe tip clean, yes/no
    - Part surface clean, yes/no
- Cooling operations status
- Measurement device axes calibration status
- Probe characteristics
    - Probe type [touch (kinematic resistive or strain gage), non-contact optical, non-contact laser, 2D, or 3D]
    - Length of shank plus ball
    - Ball type *e.g.*, spherical, elliptical
    - Ball radius/width

- Calibration status [probe axis offsets [Δx, Δy, Δz], time since last calibration]
  - Probe approach speeds for measurement [maximum, safe]
  - Probe accuracy at [maximum, average, slow] approach speeds
- Measurement device errors status
- Measure [in-situ, in-process-intermittent] command
- Physical stock/part name and number
- Measurement equipment program format
- Feature measurement sequencing rules
- Feature measurement sequence
- Part feature information types [57] (see Appendix)

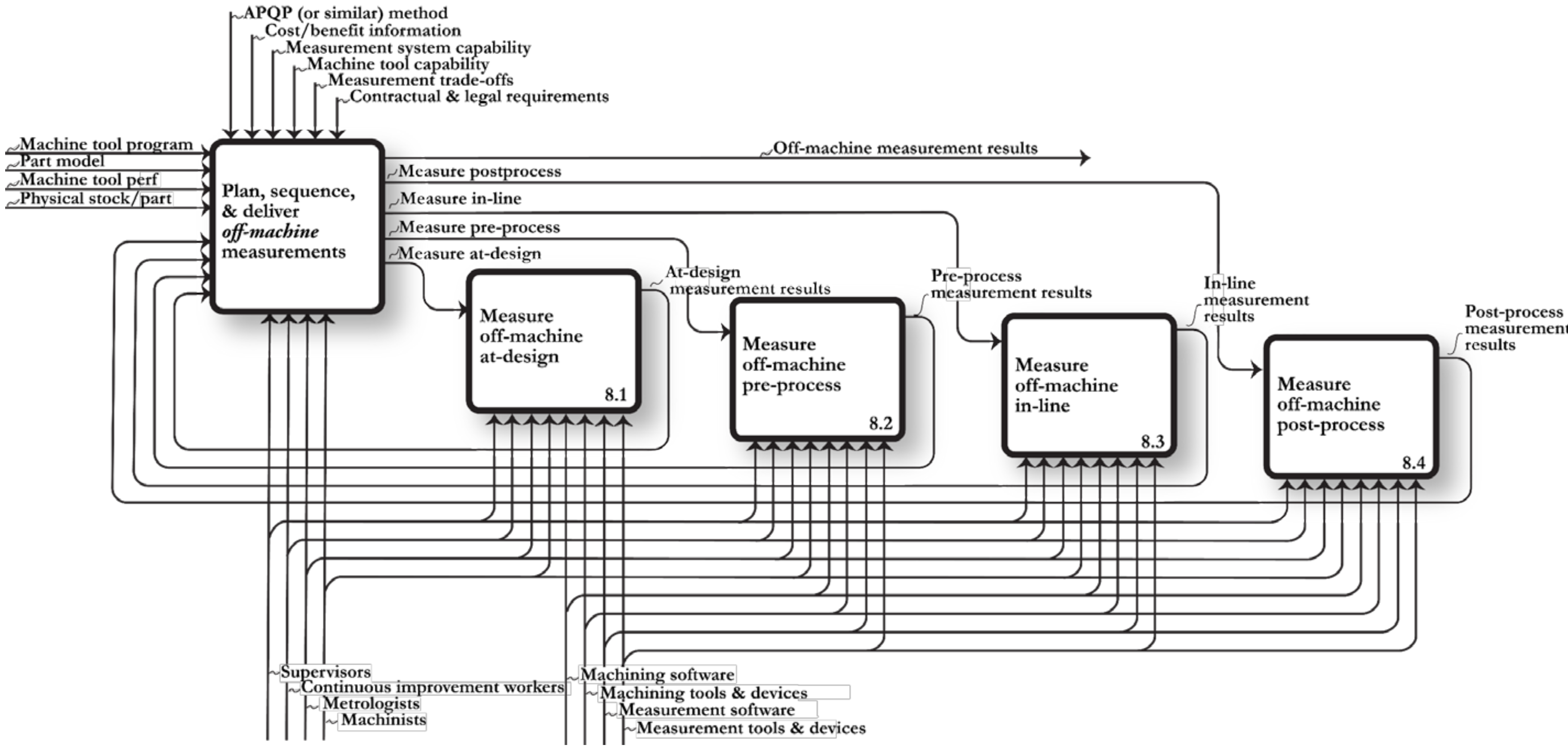

Fig. 14**:** Plan and perform off-machine measurements: a subset of activity 8 in Fig. 2, described in Sections 8.1, 8.2, 8.3, and 8.4

8 Off-machine use cases and information elements

Off-machine measurements are described in Table 1 as *a measurement performed where the location of the measurement activity is completely disassociated from location of the machining process.* These use cases are provided for context only, due to their similarity and close association with on-machine measurements. This is not intended to be an exhaustive list on off-machine measurement use cases.

8.1 Off-machine at-design use cases

8.1.1 [Off-machine, At-design] Perform a Process FMEA

8.1.1.1 Use case for performing a Process FMEA on the part model

- A *critical* element in the product/part quality process, is to develop a quality control plan. Several quality control plans have been defined and are widely used, *e.g.*, the Automotive Industry Action Group's Advanced Product Quality Planning and Control Plan (APQP) [58]. The APQP presents a high-level description of quality control plan development and describes the high-level sequence of operations to fully define the quality control plan.
- The component of the APQP of direct importance to OMM is the perform a Process Failure Mode Effects Analysis (PFMEA) [59] task. The PFMEA includes the level of criticality of the failure of each component and feature of both the machine tool, its components, and the part model.
- The effect on OMM of PFMEA is how various criticality levels will dictate the types and frequencies of on-machine and off-machine measurements performed on the part.

8.1.1.2 Information elements required to perform a Process FMEA on a part

- Non-proprietary (*e.g.*, AIAG) PFMEA standards [58], either paper-based or digital
- Proprietary (*e.g.*, corporate) PFMEA standards, either paper-based or digital
- Information elements in PFMEA standards for how the various criticality levels will affect the types and frequencies of on-machine and off-machine measurements done on the part, including
    - Part name and full description, including functionality
    - Component names and descriptions
    - Features names, descriptions, and locations
    - Criticality levels for each feature
    - Action plan for on-machine measurement
    - Process steps and function
    - Ultimate purpose of the part
    - On-machine in-process measurement failure modes
    - Potential effects of the failure modes
    - Causes, prevention, detection, and recommended action for each failure mode
    - Individuals and groups responsible taking appropriate actions and for documentation, including post-mortem on severity and occurrences

8.2 Off-machine pre-process use cases

8.2.1 [Off-machine, Pre-process] Determine the features to be measured and the part measurement frequency

8.2.1.1 Use case for determining the features to be measured and the part measurement frequency

- Manufacturers face tradeoffs between machine tool usage cost versus part feature on-machine measurement cost. They want to measure part features on-machine as infrequently as possible to increase productivity, but measure on-machine as frequently as possible for quality – to avoid or eliminate out-of-tolerance parts. Out-of-tolerance parts can generate huge costs depending on the value of the part and the importance of its function. Manufacturers perform their own tradeoff calculations, using *ad hoc* methods, best practice methods passed down from machinist to machinist, or methods involving some sophisticated algorithm.
- It is expected that developing a product quality control plan would include at least a first attempt describing which features, if any, should be measured on-machine and how. In this case, the measure on-machine output would contain at least an indication of the criticality level of features, so that a well-informed decision can be made about which features should be measured on-machine. The output of measurement sequencing rules would command the on-machine measurement activity as to which feature, and how often, needs to be measured on-machine.
- The nature of the method or algorithm chosen to measure features on-machine will greatly vary, however, for the sake of having illustrative information elements for this use case, we suggest a simple random algorithm:
  - Each feature is assigned a unique number from 1,2,…,P, where P is the total number of features.
  - Choose M total subsets of different combinations of the total number of features, P, scheduled for measurement. For example, a subset might consist of only one single feature. M would commonly be equal to 1.
  - Choose a part measurement frequency, N_i, for the i^{th} subset of features out of M total subsets, $n = [1, 2, \ldots \infty]$, where if $n = 1$, every single part is measured, and if $n = 8$, every eighth part is measured
- Another algorithm might measure features on-machine based on cost or other factors.

8.2.1.2 Information required to determine the features to be measured and the part measurement frequency

- A unique integer from 1,2,…P is assigned to each feature on part model of P total features
- M different subsets of the set of P features

8.2.2 [Off-machine, Pre-process] Modify machine tool offsets with comparator gage on a reference part

8.2.2.1 Use case for modifying machine tool offsets with comparator gage on a reference part

- A traditional CMM in a controlled environment is sometimes used to measure reference parts followed by the measurement on a comparator gage of the same reference parts in-situ with software to determine machine tool offsets which compensate for variation in environmental conditions (temperature and humidity). This operation is performed upon changes to environmental conditions.
  - Machine a reference part (this “part” can be on the fixture, a “gage pad” on the machine tool, or a “set of semi-finished features on each part”)
  - Measure the reference part on a CMM at stable temperature/humidity
  - Move the part to the machine tool and measure the part on the machine tool axes or measure the part on a Comparator (*e.g*., Renishaw Equator)
  - Use the differences in the two measurements to drive machine tool offsets
  - Machine parts, and at an appropriate periodicity, measure the reference part again on the machine tool axes or on the comparator CMM, and use the differences in measurement to drive machine tool offsets;
  - Since multiple probes are used on a given part, there commonly are routines to “datum” probes by using other probes that have already been datumed
  - Quality approval is needed on these on-machine measurement systems, and approval may require that the on-machine method be within 10% of the part tolerance and compare favorably to an alternate method
  - Another similar operation uses a calibration part – a sphere on a post – which checks for x, y, and z axis, diameter, pre-travel variation along with “performance”

8.2.2.2 Information required to generate machine tool offsets using a reference part

- Reference part name and number
- Tool offset values
- Current and past environmental measurements, e.g., [temperature, humidity]

8.2.3 [Off-machine, Pre-process] Simulate on-machine measurement program

8.2.3.1 Use case for simulating an on-machine measurement program

- Using quality measurement device software, and with a model of the machined part, an operator/programmer can manually point and click to select measurement points, which are stored in a program, then simulate the execution of the measurement program in close-up view and bird’s eye view and examine the results as they are being generated, and modify the program as required, in preparation for later execution on a machine tool with a real probe attached.

8.2.3.2 Information required to simulate an on-machine measurement program

- A set of multiple points of the form, [(x, y, z), (i, j, k)], giving nominal measurement point information from manual selection on digital CAD model

- Measurement program for simulated execution
- A set of multiple points of the form, [(x, y, z), (i, j, k)], giving actual measurement point information from a measurement simulation

8.2.4 [Off-machine, Pre-process] Ensure NC code is appropriate for stock and part

8.2.4.1 Use case to ensure NC code is appropriate for stock and part

- Ensure that the NC code loaded for execution is suitable for the CNC machine, tools, stock, and part to be machined, *e.g.*, ensure that feeds and speeds will not produce part deflection in-process.
- Simulation software should be used to determine feeds, speeds, and other parameters.

8.2.4.2 Information required to ensure NC code is appropriate for stock and part-to-be

- Tool types: [toolType1, toolType2, … toolTypeN]
- Stock material: [stockMaterialType1, stockMaterialType2, … stockMaterialTypeN]
- Location points on cutting tool path not reachable at stated feed and speed rates for stated [$stockMaterialType_i$, $toolType_j$] at location [x_k, y_k, z_k]: [[x_1, y_1, z_1], … [x_n, y_n, z_n]]
- CAD model of part
- NC code suitable for MT: [yes/no]
- NC code suitable for cutting-$tool_i$: $[yes/no]_i$

8.2.5 [Off-machine, Pre-process] Define interim part models before machining

8.2.5.1 Use case for defining interim part models before machining

- Define interim part models – unique models between the raw stock and the final part
- Prepare machining programs for these interim models
- Determine which features on one or more interim parts need to be measured.

8.2.5.2 Information elements required to define interim part models before machining

- Multiple CAD/CAM model definitions with Geometric Dimensioning and Tolerance (GD&T) fully associated with CAD geometry and features
- Model definitions are labeled in the order in which they will be machined
- 1…n levels of machining roughness associated with each feature in each model

8.3 Off-machine in-line use cases

8.3.1 [Off-machine, In-line] Perform a measurement after the machining process

8.3.1.1 Use case for performing a measurement after the machining process

- Perform a measurement, after the machining process is complete and the part is removed from the machine tool workspace, but prior to other operations on the part, like finishing processes, drilling, deburring, and assembly with other parts.

8.3.1.2 Information elements required to perform a measurement after the machining process

- A set of multiple points of the form, [(x, y, z), (i, j, k)], giving actual measurement point information from the measurement

8.3.2 [Off-machine, In-line] Perform an in-line measurement with SPC

- Measure similar part features on a sequence of parts as they are in process or at the end of process, with part measurement frequency, N_i, for the i^{th} set of features out of M total sets, $i = [1, 2, \ldots M]$, to detect any feature measurement trends toward out-of-tolerance, with the goal to avoid out-of-tolerance parts, by making timely adjustments to machine tool parameters
- Employ Statistical Process Control (SPC) software to provide user alerts, helping the machine tool operator to make timely modifications; SPC software can have real-time processing capabilities to detect errors in time for them to be fixed
- Measure equipment performance for process control

8.3.3 [Off-machine, In-line] Perform an in-line measurement with a non-contact scanning device

- Designed to be located/used on (or near) the factory floor
- May take only minutes to perform measurements (sometimes on the first article only), produce a measurement report, and take appropriate action, e.g., further processing on the part or discarding part
- Measured part can comparison back to CAD with full GD&T, depending on the measurement device capability
- "Universal" fixtures are sometimes used, avoiding new fixture building
- "Multi-reflection suppression technology[9]" has been used
- Some complex parts/features may not work well in this technology, either due to hard-to-see areas on the part or surface characteristics that do not lend themselves to optical non-contact metrology

8.4 Off-machine post-process use cases

8.4.1 [Off-machine, Post-process] Perform a measurement with environmental control with a CNC CMM

- Perform a measurement after the machining process, perhaps prior to other operations like final assembly, but typically prior to release to customer.
- Perform the measurement according to customer requirements.
- Perform a measurement in an environmentally controlled space, with respect to temperature, vibrations, particulate matter, and humidity.

9 Summary, conclusions, and future work

Two major information exchange standards organizations (the MTConnect Institute, and the DMSC) have focused their attention on either machining or standalone measurements and started around 2016 to consider on-machine measurement (OMM) information. This research is in support of this effort. We have collected, studied, and described OMM processes, revealing the input, output, resources, and control information required to execute each process.

[9] Where the system has a capability that can discern a reflected ray of light versus a ray of light directly from a feature on the part.

Detailed information elements for the "quality control plan" use case are out of scope, because the standards bodies, MTConnect Institute [7] and the DMSC [8], do not as yet have explicit APQP activities and information models in their near-term technical roadmaps. Nonetheless, the detailed information elements have already been well and thoroughly defined [58].

We categorized each on-machine measurement use case based on the orthogonal dimensions of locus and time. The focus was on two broad sets of use cases: "on-machine, pre-process" and "on-machine, in-process." Other important use cases, "in-situ" and "off-machine," were necessary because they are both closely related to OMM, and they provide a more comprehensive description of operations on or near a machine tool.

We did not cover every possible OMM use case, but trust that the use cases and information provided will form a good foundation for standards organizations. Our goal is to improve, expand, and enable digital thread dimensional metrology standards, which will enable improved software, hardware, and communications interoperability.

The OMM processes described herein have already been defined and implemented by a wide variety of manufacturers and solution providers, but with communication via different digital languages. In contrast to the use of open digital thread standards for OMM, implementations of multiple proprietary software solutions lead inexorably to unnecessary interoperability costs, since embedding OMM process information in proprietary software, usually with proprietary syntax and semantics, the costly result is always multiple proprietary measurement command and results definitions for semantically identical information elements [39, 41].

Our goal is to avoid the confusion of language and the concomitant exorbitant costs and lost opportunities caused by incompatible proprietary information formats. To help reduce these costs, standards bodies like the DMSC and the MTConnect Institute are committed to generate accurate, thorough, up-to-date, and freely-available information models, using internet-ready software language standards like the World Wide Web Consortium's (W3C) XML standard [12]. Information modeling standards for machining and dimensional measurement have been and are being developed within the MTConnect Institute and the DMSC, namely MTConnect and QIF.

It is expected that some of the OMM information elements (named and defined in Section 6) required by OMM operations are contained in the current versions of one or both standards. Nonetheless, we anticipate that there will be information elements required by the various OMM use cases, along with higher level semantic definitions for OMM not currently defined in the MTConnect and QIF standards. This expectation has motivated this research.

Further research is needed on two basic fronts: 1) to define how the information articulated for each use case would best enhance QIF and MTConnect, though it is expected to help QIF mostly, and 2) to perform a careful comparison of the OMM information elements to the information elements defined in the most recent QIF and

MTConnect versions, and make appropriate recommendations to the DMSC and the MTConnect Institute, which will include a) determining priorities and b) writing XML models for the OMM information elements that integrate seamlessly with both QIF and MTConnect. A known challenge is that, although both standards are modeled using XML Schema, MTConnect focuses on enabling real-time performance, while QIF focuses on useable and accessible file structures. Standards workers will also need to identify what elements in one standard overlap elements in the other standard and suggest resolutions.

Information requirements for diagnostic and prognostic measurements are generally out of scope in this research, excepting the measurement of a few items such as absent, broken, or chipped tools and chatter, which affect product measurement accuracy. Expanding this work to focus squarely on the information requirements for a standards-based digital thread for machine tool and measurement device diagnostics and prognostics would be useful.

While the focus of this research is on milling and turning operations, a longer-term research plan is to expand the digital thread to include other types of manufacturing. Much of the categorization of terms, definitions, and use cases in this research is expected to apply with modification to other common types of manufacturing operations beyond milling and turning, *e.g.*, electrostatic discharge machining (EDM) and extrusion. Attribute measurements are very important to manufacturing measurement, but the consideration of that work will be left to further research.

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Appendix

The following feature types are typical for part feature measurement on machined parts [57]:

- Boss: variable dimensions, commonly [radius, height]
- Chamfer: variable dimensions, commonly [width, angle]
- Cone: bottom center [x_0, y_0, z_0] normal vector = [a, b, c], [height, base radius]

- Cylinder: bottom center [x_0, y_0, z_0] normal vector = [a, b, c], [height, radius]
- Fillet: variable dimensions, commonly [radius, angle]
- Counterbore hole: bottom center [x_0, y_0, z_0] normal vector = [a, b, c], [radius, depth]
- Countersink hole: bottom center [x_0, y_0, z_0] normal vector = [a, b, c], [top radius, bottom radius, depth]
- Simple hole: bottom center [x_0, y_0, z_0] normal vector = [a, b, c], [radius, depth]
- Intersect circle: the intersection between a cylinder and a plane where the plane is perpendicular to the cylinder axis, [cylinder radius, plane height]
- Intersect line: the line formed for the intersection of two planes, [slope, y-intercept]
- Intersect plane: the plane for at the intersection of a cylinder and cone, center = [x_0, y_0, z_0] normal vector = [a, b, c]
- Intersect point: A point derived at the intersection of a plane and the axis of a cylindrical or conical face [x, y, z]
- Notch: Two parallel planes bounded by a plane perpendicular or a cylinder tangent to the side planes, with or without a planar blind end condition
- Plane: position = [x, y, z], normal vector = [a, b, c]
- Pocket: An internal extruded type closed profile, with or without a planar blind end condition
- Slot: Two parallel planes bounded by two planes perpendicular or two cylinders tangent to the side planes, with or without a planar blind end condition
- Surface: A non-prismatic face
- Width: Two parallel planes with opposing normal vectors
- Sphere: An internal or external spherical face. Radius = r, center point [x, y, z], type = internal or external
- Free surface: Non-Uniform Rational B-spline (NURB) surface model parameters