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A ROADMAP FOR METROLOGY INTEROPERABILITY

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PREFACE

The Integrated Manufacturing Technology Initiative (IMTI, Inc.) produced this report for the National Institute of Standards and Technology (NIST). The purpose of this document is to provide a roadmap that examines the current state of interoperability in the dimensional metrology process, presents a future vision for ideal metrology interoperability, identifies the key issues and major barriers to achieving interoperability goals, and poses solutions that will address the issues and remove the barriers to metrology interoperability.

Primary input for this report was gathered at the International Metrology Interoperability Summit (IMIS) and the concurrent workshop, conducted March 28-30, 2006 at NIST in Gaithersburg, MD. This document is a work in progress. Due to time constraints at the workshop, some elements of the roadmap were not completed. These elements include:

- Actions (specific tasks) needed to implement a solution to a problem or an issue,
- Assessments of technology readiness levels for proposed solutions,
- Timeframes and durations for specific solutions, and
- Estimated costs to implement specific solutions.

Many of the technical issues are controversial, and much additional discussion is needed to build consensus for recommended solutions and to capture the needed information for a comprehensive roadmap.

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Disclaimer

Certain commercial companies and their equipment, instruments, or materials are identified in this document in order to adequately specify the results of the IMIS. Such identification is not intended to imply any judgment by the National Institute of Standards and Technology concerning the companies or their products, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

1. Executive Summary

An International Metrology Interoperability Summit (IMIS) was held at NIST in Gaithersburg, Maryland, on March 28-30, 2006. Seventy experts in dimensional metrology[1] from all over the world attended the summit and participated in a structured, three-day workshop aimed at creating a roadmap document that will address dimensional metrology interoperability issues. The participants came from equipment suppliers, software solution providers, researchers, and end users, and, as such, they brought a balanced perspective to the interoperability issues.

Of the seventy attendees, 25 were end users: 8 from aerospace, 2 automotive, 5 government, 2 non-auto vehicular, 1 electronics, 1 medical, and 6 other. Thirty-one of the attendees were equipment or software vendors: 15 fixed coordinate measuring machine (CMM) software, 7 fixed CMM, 3 portable CMM software, and 6 portable CMM software. Fourteen of the attendees were from standards organizations or academia: 9 from standards groups, 3 from academia, and 3 from other groups.

This document provides a roadmap that identifies and prioritizes the technological and organizational issues facing the international metrology community. The roadmap describes proposed solutions for each major issue. The intent of the roadmapping technology used (developed by IMTI, Inc.) is to identify each major issue related to metrology interoperability, and to develop appropriate solutions for each issue. Each solution is then implemented by a set of appropriate actions (which correspond to discrete tasks or small projects). For each identified solution and action, the roadmap presents an estimated cost, time frame, expected benefits, metrics for determining successful implementation, and an assessment of technical risk.

In the short period allotted to this summit meeting, a complete and detailed roadmap was not completed. Nonetheless, a wide variety of important issues were identified and concrete solutions offered to resolve these issues. It is anticipated that one or more additional summit meetings will be needed to achieve the desired comprehensive roadmap. At the summit the following realities also hindered the development of a more comprehensive roadmap, 1) attendance and participation from automotive end users and suppliers (particularly from Europe and Asia) was weak and 2) support from the International Standards Organization (ISO) STandard for the Exchange of Product model data (STEP) community was somewhat weak. On the positive side, broad vendor participation was strong and non-automotive user support was adequate. Also, North American automotive end user and ISO STEP were all well supported in the speaker roster.

At the summit, a few issues were identified as of highest priority: 1) lack of implementations of non-proprietary data formats (such as the STEP Application Profiles (AP)) for CAD + PMI (Computer-Aided Design + Product Manufacturing Information) data downstream to inspection process planning (IPP), 2) concern about intellectual property issues and the need for formal standardization for certain emerging interface specifications (such as I++ DME (Dimensional Metrology Equipment)), 3) develop new or modify existing interface standards for use with portable metrology systems, and 4) resolve competing visions of different organizations. These and other issues and their priorities voted on by the attendees can be seen in Figure 1 and Figure 2.

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[1] *Dimensional Metrology* determines length, angular, and geometric relationships within manufactured parts and compares them with required tolerances. Dimensional metrology (synonymous with *dimensional inspection*) is inextricably linked to the overall manufacturing process and is an important element in the assessment of the quality of manufactured parts

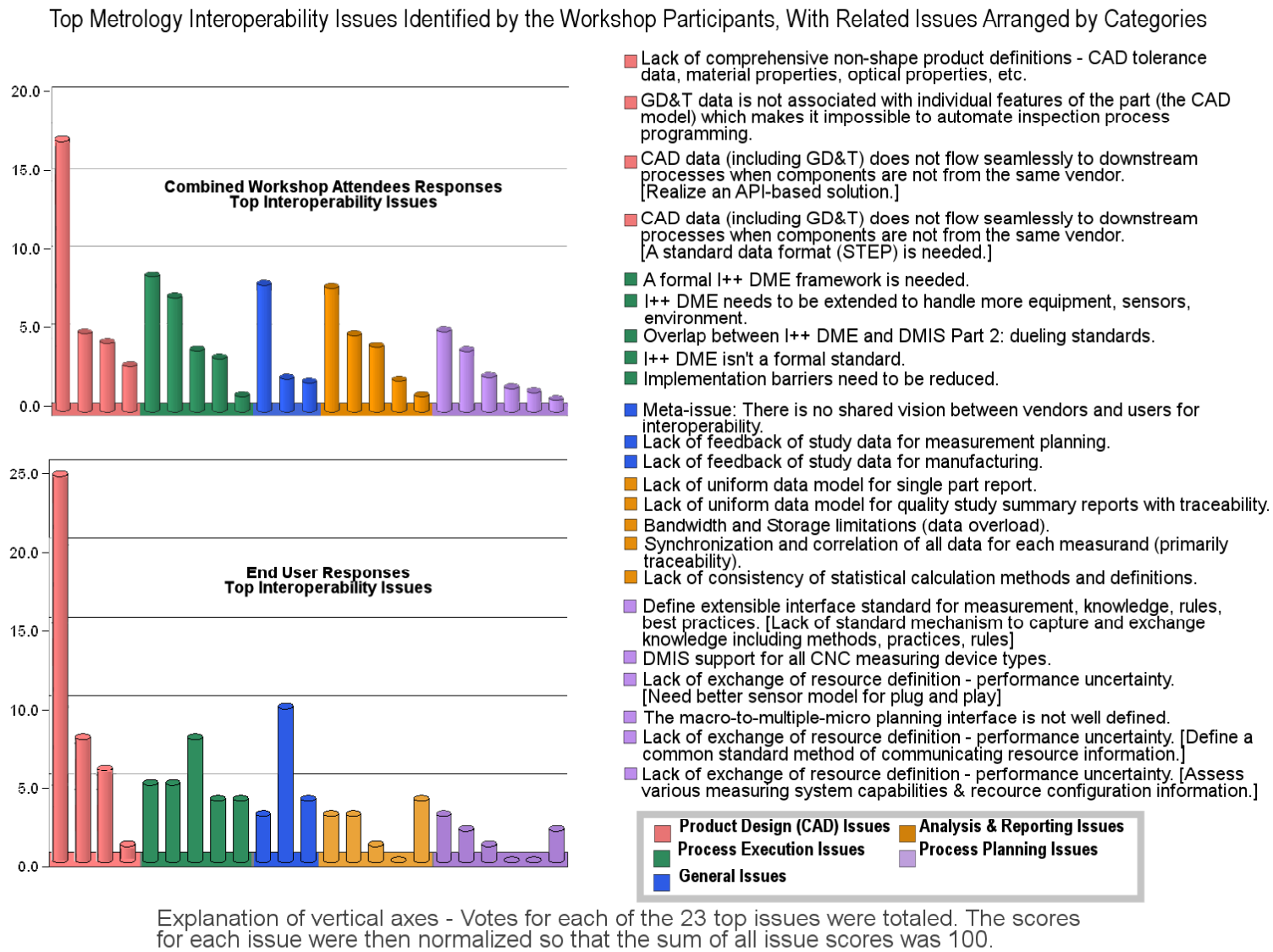

Figure 1. The top 23 metrology interoperability issues/solutions are shown grouped into five categories (see color code) and ranked according to combined input from all workshop participants. The bottom chart shows a slightly different ranking, as perceived by the end-user community.

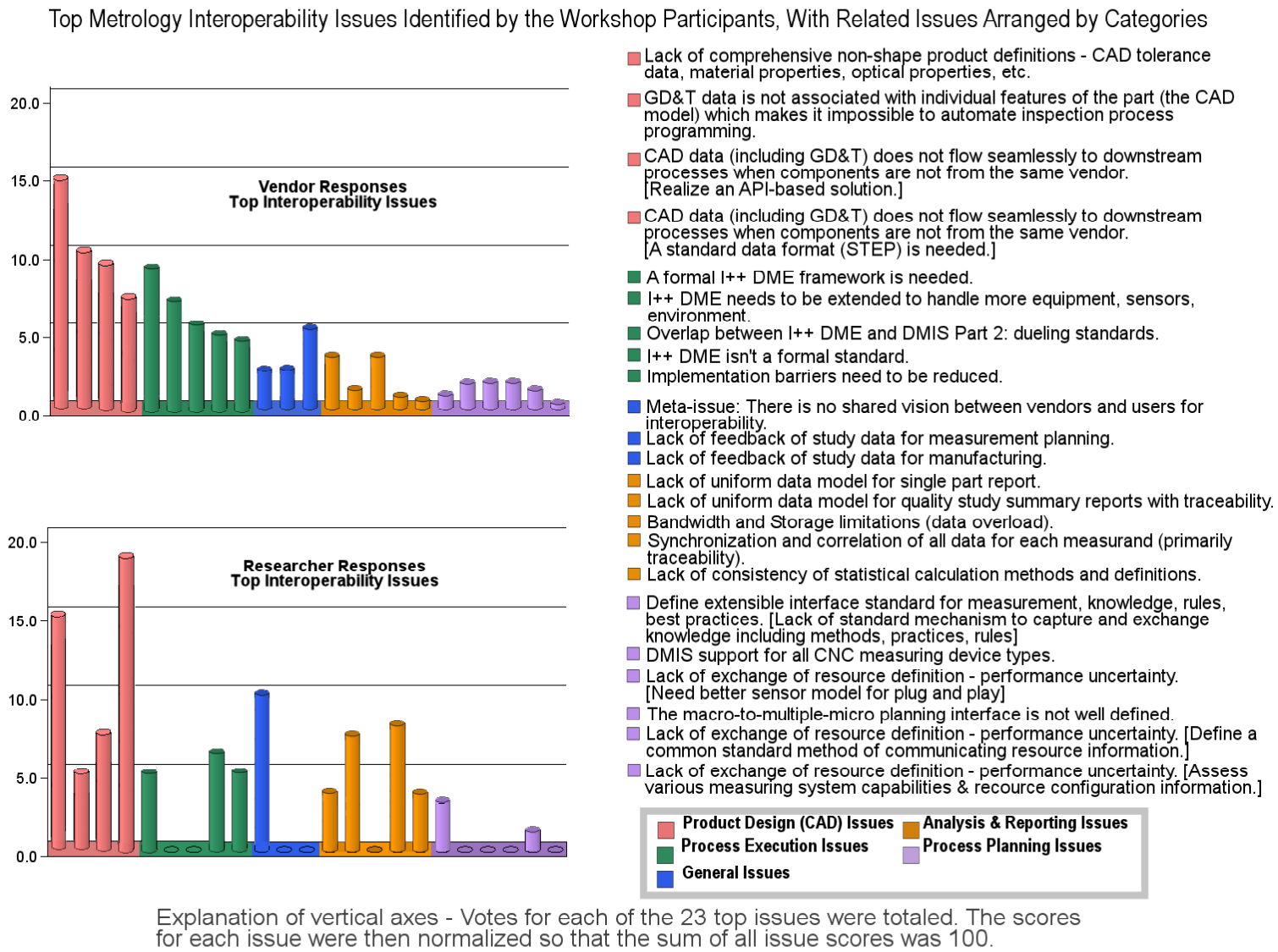

Figure 2. The same grouped issues/solutions shown in Figure 1 are ranked in a slightly different order of importance, as perceived by *vendors* and by the *researcher* community.

Dimensional metrology systems consist of distinct components, each with distinct functions, such as design (CAD), process planning, process execution, inspection hardware, and results reporting & analysis as shown in Figure 3. Multiple vendors offer products for each function. The language of communication across the interfaces between these components is typically proprietary. This proliferation of proprietary interface languages can be very costly to users, suppliers, vendors, and (ultimately) customers.

The concept of interface *interoperability* has been introduced to describe the frugality, suitability, and efficiency with which one can build systems from components. Interoperability is the ability of two system components to communicate correctly and completely with each other – with minimal cost to either component user or component vendor – where the components can come from any vendor worldwide. Interoperability reduces training costs, minimizes product development time, allows best-in-class component choices, and provides a more competitive technology provider environment – thus reducing costs for end users, technology providers, suppliers, and consumers. Interoperability is best attained by non-proprietary (or "common") interface standards (*i.e.*, protocols, formats, languages, or specifications[2]).

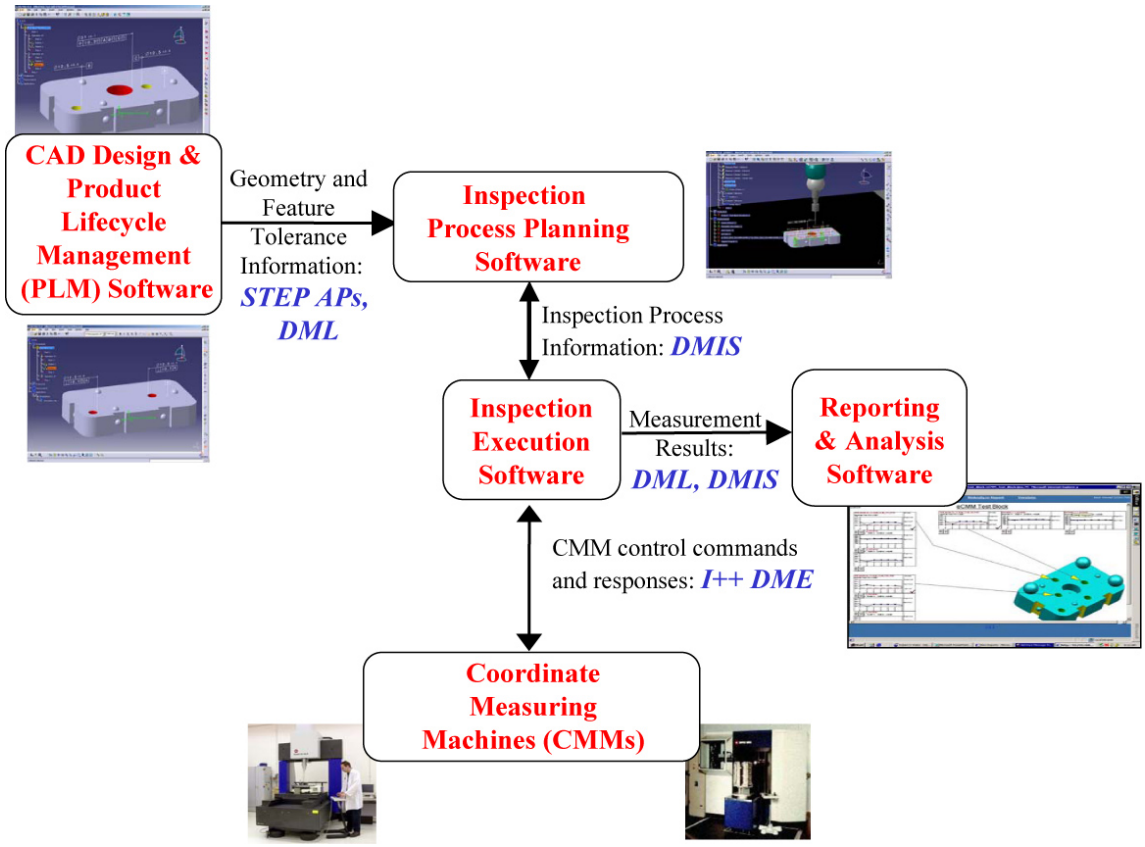

Figure 3: The current Metrology Interoperability Standards Landscape.

The total dimensional metrology process can be divided into four major interacting elements – *Product Definition*, *Inspection Process Planning*, *Inspection Process Execution*, and *Analysis and*

[2] A specification is a data definition for a particular interface that is not yet a formal standard.

Reporting of Quality Data, as shown in Figure 3. Interoperability issues can and do occur both within each of these four elements and when passing information between any two of the elements.

To some degree, interoperability can be advanced by choosing a single-vendor solution. Following this approach, all equipment and software used in the dimensional metrology process are purchased from a single vendor, or from a group of vendors, who "guarantee" compatibility between their products. The success of the single vendor approach depends on a number of factors including the size of the business, the viability of the vendor, the costs associated with a single vendor (versus a more competitive environment), and how much tier suppliers inherit end user interoperability problems.

For example, the single-vendor approach can achieve a level of interoperability for small to medium-sized businesses. However, there are drawbacks such as dependency upon the single vendor's ability to support all their clients with adequate patches and updates, dealing with specific company issues, sharing data with contractors, reduced freedom of technology choices, differing proprietary ("native") file format support (common problem with tier suppliers), and limitations in the choice of technology capabilities.

The single-vendor solution is harder to accomplish for large end user organizations with multiple – and perhaps multinational – facilities. A current trend among some large manufacturers (end users) is to require a single-vendor solution throughout their company, while requiring their tier suppliers to use the same single-vendor network. However, tier suppliers often support multiple large manufacturers, who also have single-vendor requirements from other vendors, meaning that the large manufacturers have simply passed the problem onto their suppliers. Interoperability costs by the suppliers are passed backed to the end user, so the "interoperability problem" is not solved, but just shifted around. Furthermore, end users then become beholden to their chosen single-vendor, who is now lacking the cost reduction incentives of a more competitive environment.

Interoperability choices are manifold and can be quite confusing. For example, metrology tools (hardware and software components) can range from *proprietary and closed* – not compliant with any published technical standard and not available to the public without cost, to *non-proprietary and open* – compliant with published technical standards and providing technical details of its internal structure to the technical community.

So, why not just insist on metrology tools that are standards-compliant, non-proprietary, open-source software, and then the problem is solved? For a number of reasons: 1) open, non-proprietary standards do not exist for all interfaces and those that do sometimes have overlap with other standards, 2) open, non-proprietary standards must be unambiguous, sufficiently functional, completed in a timely manner, and they must be implemented correctly by a critical mass of vendors, 3) conformance tests must be defined and used by all implementers and tied to user purchase of the implementer's product, 4) non-trivial and public interoperability tests should be performed by a critical mass of vendors, 5) a small upfront investment is required of both users and vendors, while return on that investment only comes slowly at first, 6) metrology systems users must drive the process, since vendors are not the primary beneficiaries of interoperability, 7) some metrology systems users believe they have been "burned" by standards efforts in the past that have not delivered the level of return promised, and so they are reluctant to support further efforts, 8) vendors sometimes feel that by participating in a standards effort they risk "giving away" the trade secrets that have allowed them to become successful in the marketplace, and 9) standards also reduce barriers to substitution, which vendors often see as a threat.

Even among those who are committed to seeing the use of high quality open, non-proprietary standards, there is often disagreement about the best approach to achieving component interoperability. For example, the Dimensional Measuring Interface Specification (DMIS) is the oldest, most widely implemented dimensional metrology interface standard. It has attempted to keep pace with rapid technology changes over the years, and has proposed ways to address interoperability issues. Because it is an official standard, changes to DMIS must be subjected to a rigorous approval process. For this and other reasons, vendors are varyingly reluctant to submit changes and additions to the DMIS committee. This and the fact that widely adopted conformance tests do not exist for DMIS, has contributed to a proliferation of different "flavors" of DMIS, which has impeded interoperability.

With the ISO (International Standards Organization) STEP standards, it seems that the steep learning curve, the long development time, the lack of support from major CAD vendors, and lack of conformance tests have combined to cause both users and vendors to be reluctant to support STEP, even though the STEP standards are quite mature and broad in scope, covering all aspects of manufacturing, including machining, stamping, assembly, as well as inspection.

As a result of these realities, and decisions made at an earlier summit meeting (held at NIST in May, 2000), the Automotive Industry Action Group (AIAG) Metrology Project Team (MEPT) was eventually formed to address gaps and overlaps in interface standards in the entire dimensional metrology standards infrastructure and to shorten development times for such standards. The MEPT has generated several interface specifications, including the Dimensional Markup Language (DML), an XML-based (eXtended Markup Language) interface specification for measurement results for reporting and analysis.

Also around the time of the 2000 Summit at NIST, another new organization emerged called the I++ group, which is an informal consortium of five, mostly European, automakers. The I++ group had an approach similar to the MEPT: accomplish short development times through small development groups and standardize later. The I++ DME (Dimensional Metrology Equipment) specification is currently the only output of the group, though a version of the I++ DMS (Dimensional Metrology System) specification was announced at this 2006 Summit. A major distinction between the MEPT and the I++ group, is that the development groups of the I++ are closed, contrary to the MEPT development groups, which are open to any and all participants. The short-term benefits of shortened specification development times within groups like the I++ may be compromised in the long term by the lack of control of changes by the community at large, which is allowed in a traditional standard.

During the course of the workshop, it became apparent that the most urgent issue needing to be addressed is that there are currently competing approaches to the interconnection of components/systems. There is the MEPT vision, the STEP vision, the DMIS vision, and the I++ vision. There is a mix of harmony and discord between these competing approaches. All this leads to the conclusion that there is no single shared vision between vendors and users for interoperability. Nonetheless, the presence of the rather large community of metrologists attending the IMIS seemed to express the will to identify the type and level of discord and to seek to define a way towards resolution.

After the summit and prior to the publication of this document, several activities have commenced in response to issue/solution pairs identified at the summit. Several positive results have come out of the IMIS, including, 1) Concern over intellectual property issues at the summit involving the DMIS and I++ DME have resulted in positive activity toward the resolution of intellectual property issues, 2) CAD interoperability issues are now being addressed through a pilot project, which has had

substantial vendor participation, and through participation in the SME CAD Interoperability Conference, at which NIST led a workshop on Downstream CAD, 3) NIST organized and led a workshop/panel discussion, entitled, Interface Standards for Portable Metrology Systems, at the Coordinate Metrology Systems Conference (CMSC) 2006, attended by around 100 portable metrology professionals, and 4) an important pilot project has begun as a result of this interaction between laser tracker vendors, NIST, and software vendors to exercise I++ DME on this interface.

2. Introduction

An International Metrology Interoperability Summit (IMIS) was held at NIST in Gaithersburg, Maryland, on March 28-30, 2006. Over 60 experts in dimensional metrology from all over the world attended the summit and participated in a structured, three-day workshop aimed at creating a roadmap document that will address dimensional metrology interoperability issues. This document is the first step in creating the roadmap. Although all four breakout groups used similar techniques for identifying key interoperability issues and solutions, the level of detail achieved varied greatly among the groups. The level of detail in the resulting roadmap reflects those differences. It is hoped that this initial document will evolve into a polished roadmap that can be used to systematically solve the multitude of interoperability issues that were identified during the workshop.

Background

Metrology is the science of measurement and its corresponding accuracy, precision and uncertainty. To measure is to ascertain the numerical value, in terms of some physical unit, to a quantity, quality, magnitude or dimension. To inspect is to determine compliance to a specification (e.g., tolerance) by measuring, gaging, or other means of examination. Often, measurements are performed to verify and inspections are performed to accept.

In its most basic form, *Dimensional Metrology* can be thought of as the determination of length, angles, and other geometric relationships. In the world of manufacturing, *dimensional measurement and dimensional inspection* are synonymous with *dimensional metrology*. Today, industry typically uses coordinate metrology (e.g., coordinate measuring machines) as the preferred method for performing a dimensional inspection task.

Figure 4. Interoperability issues arise, in part, due to the myriad categories of software available with today's metrology equipment.

Standards for *Geometric Dimensioning and Tolerancing* (GD&T) have been devised in an attempt to analyze the quality of manufactured components in a consistent manner through dimensional inspection. However, there is more to the dimensional inspection process than just analyzing the dimensions and tolerances of manufactured components. The *product design* specifications must be taken into account in *planning the inspection process*; the inspection process must be *executed* to obtain appropriate inspection data; the data must be *analyzed* and the results *reported* in a way that accepts/rejects the component and provides feedback to the manufacturing process that produced the component.

The concept of interoperability is introduced to address the issues that complicate the inspection process. Interoperability is defined as “the ability of two system components to communicate correctly and completely with each other – with minimal cost to either component user or component vendor, where the components can come from any vendor worldwide.” Component-to-component

interoperability reduces training costs, allows best-in-class component choices, and provides a more competitive technology provider environment – thus providing the promise of reduced costs for OEMs, technology providers, suppliers, and consumers.

Interoperability issues are almost always related to the software that controls a component or allows the component to interact with some other component or other piece of software. Software can be categorized in several ways, as shown in Figure 4. Solutions that use open and non-proprietary interfaces have economic and technical superiority over proprietary solutions if the following conditions are met:

- An open, non-proprietary solution must exist.
- It must be sufficiently functional.
- It must be malleable to changes in technology.
- It must allow vendors to introduce new technologies over the interface without revealing the details of the technology to competitors.
- Users must be able to verify (through compliance tests) a vendor's claim to compliance.
- It must be implemented worldwide.

If an open, non-proprietary solution does not yet exist, the community works toward it, and lives with proprietary solutions for the time being.

The dimensional inspection process is a subset of the overall manufacturing process and the two processes are inextricably linked. Numerous software and hardware systems have been devised to support these processes and, unfortunately, lack of interoperability abounds. In a perfect dimensional metrology world, the information needed to completely and unambiguously define the dimensional characteristics and requirements of a part should be contained in the product definition knowledge base, and should be available for planning the inspection process. Information contained in the inspection process plan should be sufficient to completely and unambiguously define the dimensional inspection requirements of the component. The output of the inspection process plan should provide all the information needed to perform the measurement of the component, independent of the brand or type of measuring equipment used. The measurement results should be stored in a neutral format that can be made available to a variety of analytical and reporting tools that determine whether the quality of the part is acceptable. Analysis and reporting tools should be flexible enough to present metrology results in a variety of ways to suit the specific needs of the end user. The results from the analysis of inspection data should also be available as feedback to upstream manufacturing processes and feed-forward to downstream manufacturing processes. As shown in Figure 5, the dimensional inspection process can be arbitrarily divided into four major interacting elements that embody the above capabilities

- Product Definition,
- Inspection Process Planning,
- Inspection Process Execution, and
- Analysis and Reporting of Quality Data.

Interoperability issues can and do occur both within each of these four elements and when passing information between any two or more of the elements.

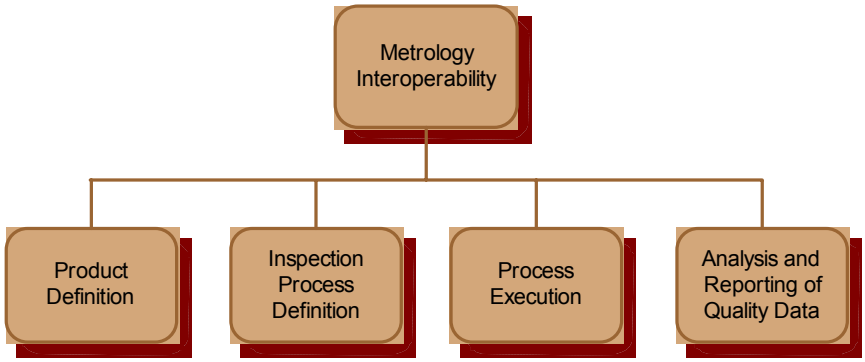

Figure 5: Lack of interoperability abounds between the four functional components that comprise the dimensional metrology process.

Metrology interoperability has been recognized as a desirable goal for at least a decade, and several standards have been proposed and implemented with varying degrees of success in pursuit of that goal. Figure 3 shows the current "landscape" for interoperability in dimensional metrology. Four main interfaces are illustrated:

- CAD Geometry, Features, and Tolerances,
- Inspection Process Information,
- CMM Control Commands and Responses, and
- CMM Measurement Results Output.

The principal applicable standards or specifications are: STEP, DMIS, I++DME, and DML. Major stakeholders in metrology interoperability include government and academic researchers, end users, equipment and software manufacturers, and integrated solutions providers. Some of the principal stakeholders are shown below.

- *National Institute of Standards and Technology (NIST)*, providing advice, support, and active participation at the task level for many years. NIST develops tests for verifying compliance of implementations to each standard. NIST performs detailed standards analysis, as requested by the industry. NIST also maintains a metrology interoperability test bed in Gaithersburg, MD, that is actually part of a distributed test bed with active participants worldwide.
- Metrology *Project Team (MEPT) of the Automotive Industry Action Group (AIAG)* – Also known as MIPT, or Metrology Interoperability Project Team) – Consisting of users and vendors working together to achieve interoperability of software and hardware in automated metrology in order to reduce product development cycle time and reduce manufacturing costs, this organization is an "umbrella" group that oversees all the metrology interface standards efforts worldwide, without competing with existing standards organizations such as the Dimensional Metrology Standards Consortium (DMSC). The MEPT seeks to harmonize standards overlaps and fill in gaps where they exist.
- *Dimensional Metrology Standards Consortium (DMSC)* – The DMSC is an accredited standards-making organization that grew out of the DMIS National Standards Committee (DNSC) and has assumed responsibility for the maintenance and support of the DMIS Standard. However, the new mission of this group has expanded to address the development of other dimensional metrology standards as well as their interoperability issues.
- *DMIS Standards Committee (DSC)* – An organization under the auspices of the DMSC that maintains and enhances the Dimensional Measuring Interface Standard (DMIS) for both ASME and ISO. The DMIS standard is currently version 5.0.

- *European DMIS Users Group - (EDUG)* - A not-for-profit organization for the purpose of furthering the acceptance of and promoting the use of DMIS in Europe. The organization also provides a a unified voice to further enhancements into the DMIS standard
- *International Association of CMM Manufacturers (*IA.*CMM)* – The purpose of the Association is to support and to promote the interests of the worldwide industry of coordinate measuring machines technologies. It provides support for the I++ group, which develops and maintains the I++DME Specification.[i]
- *I++ group* – an informal consortium of automakers (Audi, DaimlerChrysler, BMW, Volkswagen, and Volvo), which has been developing the I++ DME (Dimensional Metrology Equipment) specification and which has plans for other dimensional metrology system interface specifications

Over the last 25 years, billions of dollars have been invested in automated manufacturing solutions, and great progress has been made. Today, under carefully controlled conditions (using a test product with limited complexity), it is possible to extract an inspection process plan from a product definition model, use this plan to generate and execute a more-or-less device independent inspection program, and report the results in a more-or-less neutral format. However, such a feat is still at the "demonstration" or "proof-of-principle" stage. Much work and many problems remain before seamless interoperability is achieved on a routine basis. Perhaps the biggest problem is that there is more than one set of software tools to do the job, and the tools often do not work in harmony.

The Interoperability and Standards Challenge: Achieving critical-mass support for open, non-proprietary standards is a challenge. One important reason is that standards development requires a substantial up-front investment of time and resources from the parties involved (e.g. users, suppliers, vendors, and standards professionals). Years may pass before any financial benefits are realized from these standards.

As a result, standards development stakeholders must realize that their investments will pay off. However, this delayed benefit is partly why a single-supplier-network approach becomes appealing. Establishing a single-supplier network achieves temporary interoperability without significant up-front cost. However, the argument of many is that the single-supplier-network approach to alleviating interoperability problems typically has hidden costs – such as constraining best-in-class, causing increased prices, requiring file translation and retraining, and surrendering your process to an outside vendor.

Unfortunately, support for open, non-proprietary standards has waned even among experienced professionals, since several standards efforts have either failed or been weakened by a variety of factors. Today we know that these factors include lack of worldwide support, lack of conformance tests, insufficient standards maintenance, insufficient functionality in the standard, and lack of timeliness.

If we think a standards approach is most cost-effective in the long run, the entire community needs to address such non-technical barriers head-on with creative solutions. A roadmapping exercise should provide help in defining such solutions and the actions necessary to realize the solutions.

The International Metrology Interoperability Summit (IMIS)

An International *Metrology Interoperability Summit* was hosted by NIST on March 28-30, 2006 in Gaithersburg, Maryland. Sponsors for the summit included the AIAG MEPT and the DMSC. These sponsors joined forces in a "volunteer army" to bring the summit to fruition. The representatives formed an ad-hoc IMIS steering committee. The steering committee provided the planning and

coordination for the effort, and will play a continuing role in reviewing, maturing, and implementing the resulting roadmap. The overarching goal of the summit is to highlight key needs, reach resolution/consensus on important issues, and to develop a roadmap that, when implemented, will deliver interoperable solutions for metrology applications. More specifically, the stated goals of the summit are:

- To gather together dimensional metrologists and decision-makers with a common desire to enable metrology system component interface interoperability.
- To assess the current status of metrology interoperability and build a roadmap defining future activities.
- To seek greater unity with organizations worldwide, working together efficiently and effectively to accomplish a common agenda.

A roadmap is a useful tool for identifying and seeking consensus on key issues requiring resolution. It is also useful for creating a work-breakdown structure by prioritizing the issues, assessing the scope of work needed to resolve them, and estimating the timeframe required to implement solutions. Among the more important issues that were identified prior to the summit:

- DMIS is the most mature international standard in our domain. DMIS is bidirectional. In one direction, DMIS plays two roles, one as a computer-readable interface language and another as a human-readable programming language with which humans can create and store an inspection program. Recently, we have seen a market trend that impacts the role of DMIS. Users increasingly "program" a CMM through a more or less graphical interface. They are, in essence, creating a high level process plan; they apply GD&T and inspection planning information to the CAD model and the lower-level inspection plan and execution are generated more-or-less automatically, within the same software package. Surely there will be a need for DMIS for a plethora of systems currently in production. However, switching our headlights to high beam on a roadmap, should we anticipate that the interface DMIS is written for, the Dimensional Measurement Planning (DMP) interface, might go "underground?" Which is to say, should we expect that there would cease to be distinct products on either side of the DMP interface, obviating the need for open, non-proprietary standards at the DMP interface?
- The AIAG MEPT has been working on open, non-proprietary metrology results data standards such as DML. ISO STEP has developed a similar standard in STEP AP219. Open, proprietary standards exist, as well, for example, QML (Quality Markup Language). Can we achieve worldwide agreement on what standards to support or develop that relate to quality output data, including dimensional metrology measurement results?
- What is the preferred way to define CAD + GD&T information? Will STEP AP 203 edition 2 suffice? Should DML or STEP AP 219 fill this gap? Will this interface also go "underground?" Namely, will GD&T assignment to CAD always occur within a single vendor's software package, again doing away with the need for open, nonproprietary standards at this interface? Could one of the CAD vendor's proprietary standards become an open, non-proprietary standard that has the support of the whole community?
- What should be our attitude towards the ISO STEP standards as a dimensional metrology community, because either 1) they take too long to develop (viz. AP219), 2) too much of a learning curve is required to implement, or 3) we are too small a community to effect a change (e.g., to get CAD vendors to support AP203 2nd edition)?
- To consider expansion of our efforts to embrace other domains such as CNC machining and assembly, vision-based CMMs, and non-contact, manual CMMs:

- CNC machining and assembly: On-machine inspection for in-process correction of machining parameters is becoming more common. The definition and encoding of feature and tolerance information is similar to that required by the metrology function. In spite of this, there has been very little fruitful synergy between the machining, assembly, and metrology domains.
- Non-contact manual CMMs and vision-based CMMs: The use of semi-manual and non-contact CMMs (laser trackers and articulated arm CMMs) is growing in both aerospace and automotive sectors. Vision-based CMMs have not traditionally been included in interface standards efforts for CNC CMMs. Several questions need to be addressed by the entire dimensional metrology community:
  - Are these systems ready for interface standards? Do users want or need them?
  - Will the standards developed for CNC CMMs apply to semi-manual and non-contact CMMs?
  - Are separate interface standards needed for semi-manual and non-contact CMMs in addition to the existing and emerging interface standards for CNC CMMs?

Workshop Structure

Attendees of the International Metrology Interoperability Summit also participated in the metrology interoperability workshop at NIST. The three-day summit/workshop brought together dimensional metrology experts and other stakeholders from all over the world. It provided an opportunity for identifying key issues affecting metrology interoperability, proposing high-level solutions that address those issues, identifying barriers to the implementation of the solutions, and ranking the solutions in order of perceived importance. Materials generated in the workshop were used to construct the roadmap described in this document. In order to fully understand and appreciate the roadmap, it is necessary to understand the methodology and terminology used at the workshop to compile the information contained in the roadmap. Please refer to Appendix 4.4 for a detailed explanation of workshop methodology.

Objectives

It is obvious that a lot of work has already been done to foster interoperability. What is needed now is a concerted effort:

- to identify gaps and areas of overlap,
- to *harmonize* existing standards and practices where apparent conflicts exist,
- to create new standards and extend existing standards that will address new and emerging issues, and
- to utilize the resulting body of standards and practices to achieve seamless metrology interoperability.

Also needed is for users of metrology systems to lead all these efforts, to ensure that the outcome suits their needs. The purpose of this roadmap document is to provide a framework that presents the above ideas in a clear and concise manner. Such a framework must identify and describe interoperability issues, provide a clear vision for the future, and define solutions for key issues that will overcome barriers to the successful implementation of metrology systems that are truly interoperable. The roadmap will also provide the basis for a strategic investment plan that maximizes the resources of all stakeholders.

3. Technology Plan

Elements of the technology plan for metrology interoperability are presented for each of the four breakout groups (*Product Definition*, *Inspection Process Definition*, *Inspection Process Execution*, and *Analysis and Reporting of Quality Data*), as well as for crosscutting issues that affect the entire dimensional metrology process. Activity models are very useful tools for visually depicting the major elements of a process at a high level, and analyzing the process by breaking it down into its key activities. The activities are presented in a flowchart format that displays interactions such as *inputs* from preceding activities or processes, *outputs* to subsequent activities or processes, and *decisions* or *branches* that are based on conditions encountered within a process. The activity model (also called an activity diagram) can also depict boundaries between activities and, at a higher level, between processes. It is across these boundaries that interoperability issues occur. Activity diagrams are used in the following sections of this document to provide a quick overview of the key activities and relevant interoperability issues identified by the four breakout groups during the workshop.

During the final day of the workshop, each participant was given a ballot comprising a list of the top interoperability solutions identified by the breakout groups, and ten “metrology dollars.” Dollars were used to vote on the solutions they believed to be most important. Each participant could allocate up to three dollars to any given solution. In a few cases identically worded solutions were proposed for more than one issue, which made the voting process confusing. In those cases the solutions were paired with their corresponding issues. The ballots were grouped according to whether the participant was an end user, a metrology researcher, or an equipment manufacturer. The tabulated results established a rank for each of the 23 top solutions. The results were tabulated for each group (end user, researcher, or manufacturer) and for the combined groups. The overall ranking was determined by the vote totals from the combined group, normalized to a scale of 0-100. Related issues/solutions were grouped into one of categories (Product Design – CAD, Process Planning, Process Execution, Analysis and Reporting, and General Issues). Results are shown in Figure 1 and Figure 2. Approximately 29 percent of votes cast

by the workshop participants were for Product Definition (CAD-related) issues, which was the largest category. However, issues related to the other three breakout categories also had a sizable distribution of votes. Approximately 12 percent of the votes cast were for general issues that either spanned multiple categories, or did not clearly fit any of the four categories.

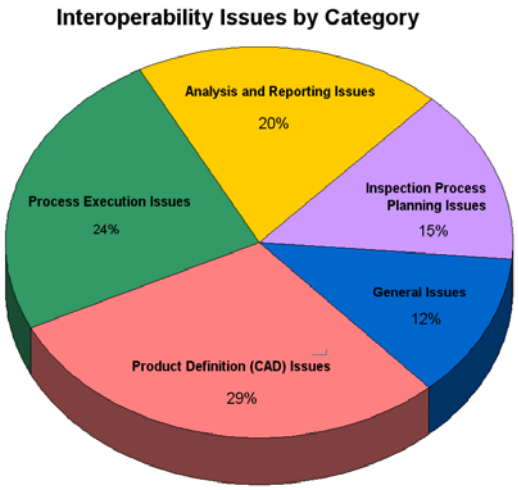

Figure 5. The pie chart shows the aggregate of votes cast for issues in each of the four breakout categories, plus a general category.

3.1. Technology Plan for Product Definition

Participants in the product definition group included Stephen Anderson (Renishaw), Conrad Bock (NIST), Dave Callaghan, (IQL), Tom Kramer (NIST - session scribe), Kevin Legacy (Zeiss), Len Slovensky (Northrop Grumman), Tom Melson (Boeing), Andrew Moore (QVI), Troy Niehaus (Metronor), Bill Rippey (NIST - session facilitator), Bill Tandler (Multi Metrics), and Jerry Udy (Spatial).

The Product Definition breakout group created the detailed as-is (current state) activity model shown in Figure 5. From the perspective of dimensional metrology, the most important function of the *product definition* activity is to provide sufficient information to permit the automatic generation of an inspection plan. Thus, the output of the *product definition* activity should flow seamlessly into the downstream *inspection process definition* activity. Such information must include things like part geometry, features, tolerances, and relevant manufacturing information, such as surface finish and material properties.

Current-State Assessment for Product Definition

The right side of the activity diagram in Figure 5 shows some of the key functions that occur during the early stages of part definition activity. Figure 6 shows the product definition activity from the perspective of an end user who needs to define an inspection process using the output of the product definition software. It gives a clear indication of some of the interoperability challenges between the two activities. The first metrology-related interoperability question that arises in the product definition activity is "*Can product manufacturing information (PMI) be embedded in the CAD model (PMI includes elements such as geometrical dimensioning and tolerancing (GD&T), surface finish, optical properties, and material properties)?*"

Furthermore, can we embed all this information using an open, non-proprietary data format, like the STEP standard? CAD software vendors are currently working on this problem and generating successful solutions, but with proprietary data formats exclusively. Perhaps, one of these promising proprietary data formats could form the basis for a new open, non-proprietary standard. Perhaps, one proprietary data format will emerge as a *de facto* standard, in the way that computer operating system software has *de facto* standards. An example of this in the CAD domain is the quasi-proprietary interface standard, JT, which is defined to allow the visualization and manipulation of complex 3D geometry of parts and assemblies[ii].

In today's world, PMI information is only limitedly available in proprietary software, and there are *no* CAD product implementations of PMI information using non-proprietary standards. Looking at the simplest case, where the product consists of a single monolithic part, the part must be decomposed into geometric features. Dimensions and tolerances must then be assigned to a geometric feature, or set of features. Datum features must be defined in such a way that they are appropriate both for

manufacturing the part and for inspecting it. Surface texture information must be included in the model, along with relevant information about the orientation or *lay* of the surface texture to be measured. Accurately extracting this type of information would require interaction with the manufacturing process plan, which defines the process used to create the surface that is to be measured. Therefore a process definition that defines the manufacturing and measuring process must be interconnected with elements within the product definition. Furthermore, the processes require resources (sensors, fixtures, machines), and therefore a resource definition that supports the process definition must be represented. Realistically, this doesn't happen in today's world. Figure 5 is an activity model that focuses on this specific problem. It is a rough, but reasonably accurate, portrayal of today's interoperability problems between product definition products and downstream manufacturing processes.

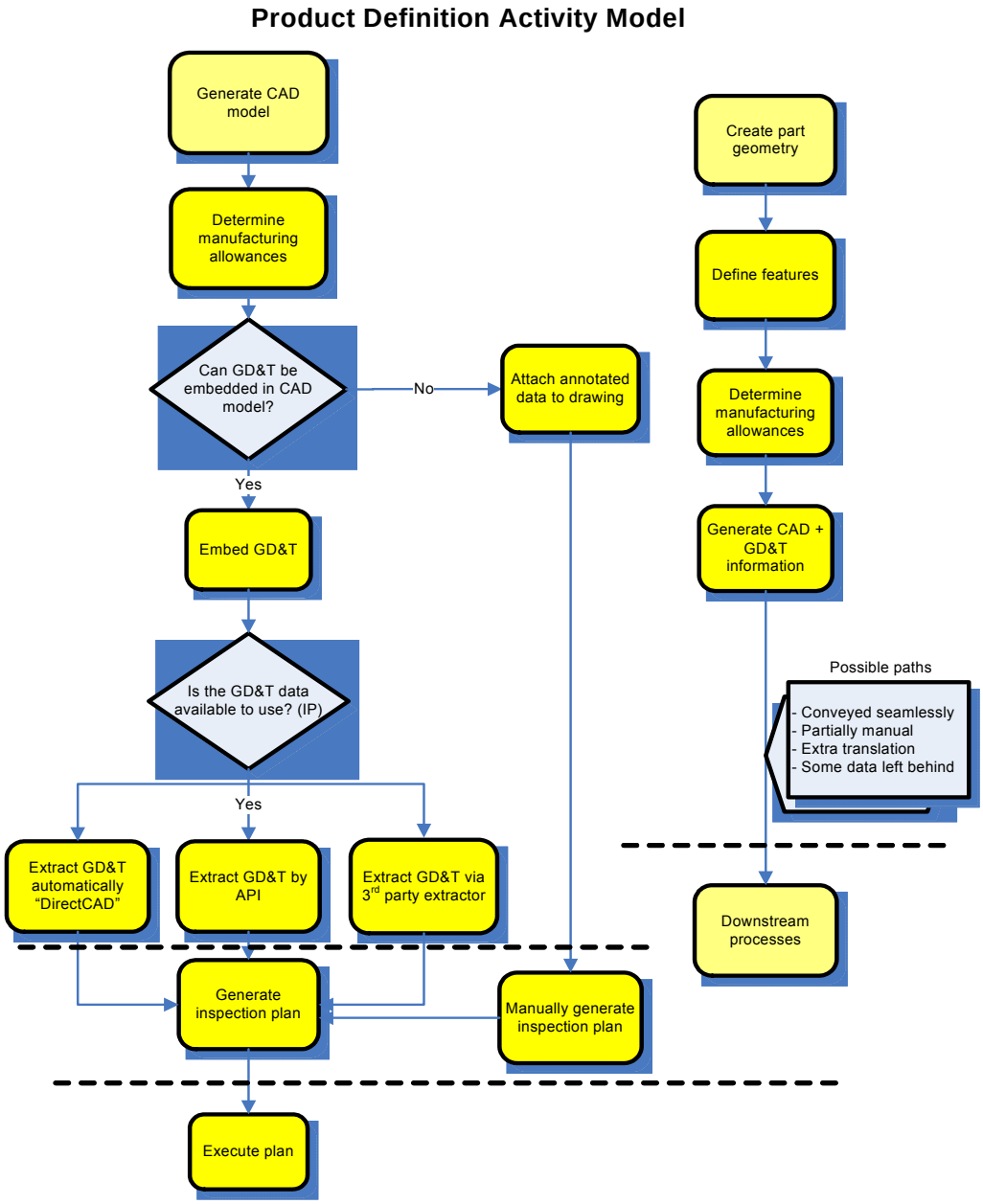

Figure 5: The numerous alternate paths shown in this as-is activity model for product definition are indicators of interoperability issues. The horizontal dotted lines show the boundaries between downstream processes.

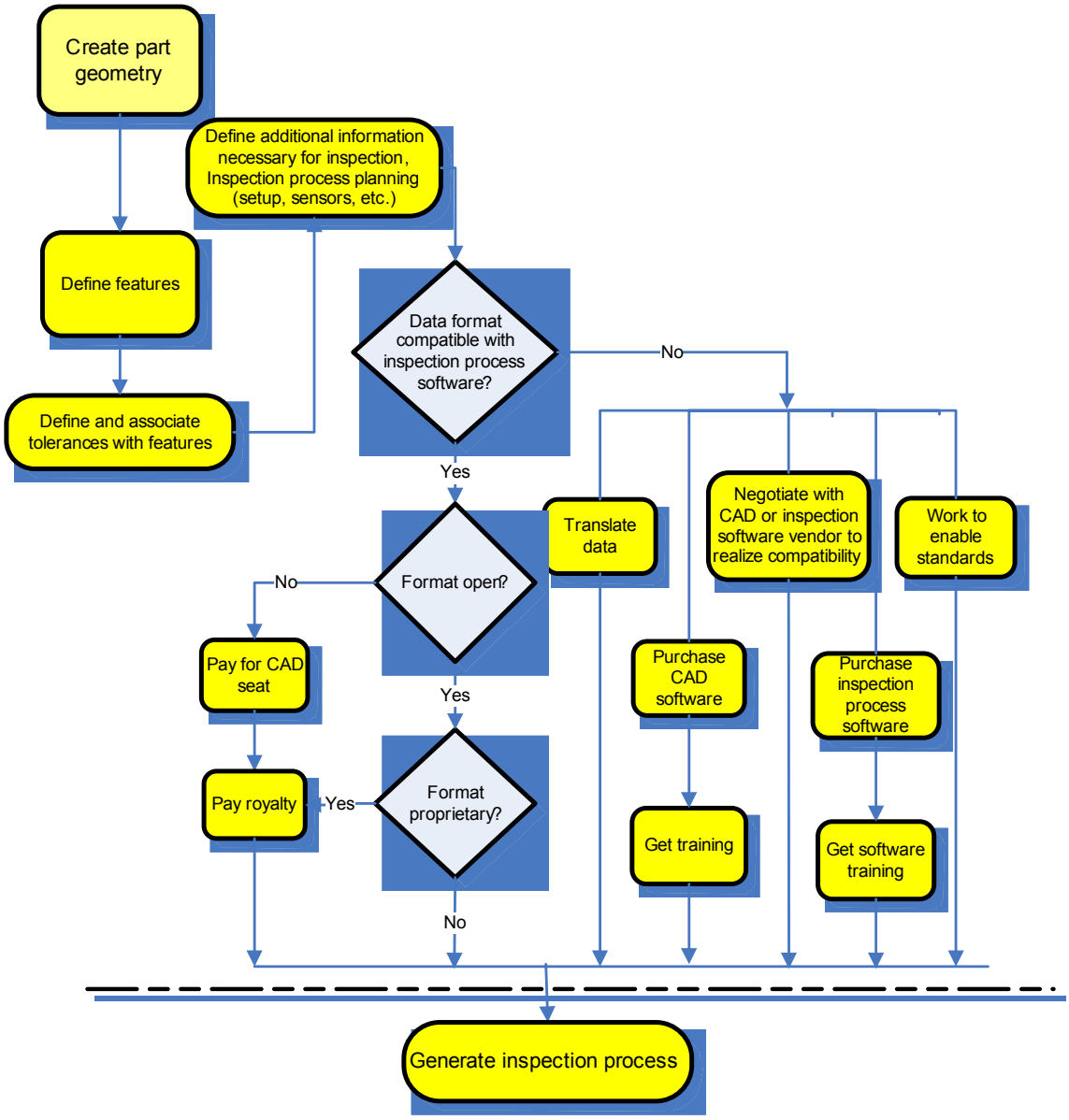

Figure 6: This activity model shows clearly shows the interoperability challenges between product definition and inspection process planning products.

Assuming that GD&T *can* be embedded in the CAD model, an important issue which affects interoperability is *"Will end users and suppliers be successful in persuading CAD vendors to encode part geometry + PMI in an open, non-proprietary file format, sufficiently rich enough to allow the automatic generation of a complete process plan?"* The current common business model for CAD vendors is to define a closed and proprietary interface, where the process planning vendor (and ultimately, the user) must pay for access to select portions of geometry + PMI (through API interfaces), which may or may not be saved to file. Also, common is for end users to require suppliers to read and write design data in native (proprietary) file formats, and the type of proprietary file format varies from end user to end user. This may allow each individual end user to create the appearance of interoperability, but, in fact, interoperability costs are merely passed onto their suppliers, who must support multiple proprietary file formats required by the various end users they support.

Yet another issue, due to a variety of circumstances, is that software translators between different proprietary CAD + PMI formats may continue to exist and thrive for some time to come. The question then is "How should standards bodies respond to these proprietary realities? Should they be resigned to the current status quo and perhaps define other standards based on current *de facto* standards?" The Product Definition group asks "Is there a path of migration from proprietary to non-proprietary interface standards?" A possible solution is to adopt the OMG model for standards development, where the vendors compete with their proprietary standards and vote for the one they consider the best, which is then chosen as the basis for a new open, non-proprietary interface standard.

The ISO STEP standards have made a heroic effort toward achieving interoperability on the CAD interface, particularly for the interface between CAD and machining process planning. There has also been substantial work on the interface between CAD and inspection process planning, for example with STEP AP203 edition 2, STEP AP 224, and STEP AP 219. However, there is a strong negative perception in the dimensional metrology community relating to the STEP standards, that 1) they are too hard to understand and therefore difficult to implement, 2) they have, as in the case of AP 224 and AP 219, virtually no implementations, nor do robust and well-exercised conformance tests exist, casting doubt that the standards can produce interoperability even if the steep learning curve is overcome, and 3) the ISO STEP standards process is too slow, and several standards efforts (e.g., MEPT and I++) have pursued another model, namely, develop a specification quickly with a small team of recognized experts, then only when the specification is reasonably mature and has many implementations, release the specification to a standards body like the DMSC (Dimensional Metrology Standards Consortium) or ISO (International Standards Organization).

Interoperability Issues for Product Definition

Table 1 summarizes the top interoperability issues identified by the product definition group. Following the table, recommended high-level solutions and (where available) more specific actions are presented for each issue.

Table 1. The top metrology interoperability issues, as identified by the product definition group.

Top Product Definition Issues
CAD data (including GD&T) does not flow seamlessly to downstream processes when components are not from same vendor.
GD&T data is not associated with individual features of the part (the CAD model), which makes it impossible to automate inspection process programming. If GD&T information is expressed as annotations in CAD files or as notes on drawings, it is not available to automated computer processes that can use it.

It is difficult if not impossible to know if a vendor truly supports a standard as advertised. When a vendor claims that its product conforms to a standard, there is often no means of certifying that the product actually does conform to the standard as claimed.
There continues to be divergence in the use and interpretation of GD&T standards both within the U.S. and at the international level. Some major companies have adopted internal variations in the way that they interpret and apply the standards. It is believed that this practice will result interoperability problems in the near future. The standards effort must be international, involving multiple government standards organizations.
Crosscutting Issue: There are currently no "consensus" approaches to the interconnection of components/systems. The "big picture" needs to be defined before unified efforts can be developed to solve this important problem. There is no shared vision between vendors and users for interoperability

Issue 1: (See the ***Crosscutting Issue 1***.)

Issue 2: CAD data (including GD&T) does not flow seamlessly to downstream processes when components are not from same vendor.

> ***Solution 1:*** Realize an API-based (Application Program Interface based) solution such as AIMS (Advanced Integrated Mathematical System) or Honeywell FM&T's FBTol (Feature-Based Tolerancing). Boeing gives away the "kernel" software for AIMS, and publishes the API specification.
>
> ***Solution 2:*** Realize a standard data format, such as STEP (**ST**andard for the **E**xchange of **P**roduct model data).

Issue 3: GD&T data is not associated with individual features of the part (the CAD model), which makes it impossible to automate inspection process programming. If GD&T information is expressed as annotations in CAD files or as notes on drawings, it is not available to automated computer processes that can use it.

> ***Solution 1:*** The CAD community puts associated GD&T in their data formats (beyond annotations) as a matter of standard practice. This requires consensus and is related to the crosscutting issue of a lack of business case consensus described in the *Crosscutting Issues* section below.
>
> ***Solution 2:*** End users must be more emphatic and aggressive in defining best practices and needs to CAD vendors.

Issue 4: **It is difficult if not impossible to know if a vendor truly supports a standard as advertised. When a vendor claims that its product conforms to a standard, there is often no means of certifying that the product actually does conform to the standard as claimed.**

> ***Solution 1:*** Certification bodies must be created or identified, and certification test methods must be required and created or identified for products.
>
> > ***Action:*** NIST (or other government-sanctioned organizations at the international level) should consider changing their missions to include the performance of standards conformance tests that will certify product conformance to standards or to support certification more directly.
>
> ***Solution 2:*** Use conformance classes in the standard.

Issue 5: There continues to be divergence in the use and interpretation of GD&T standards both within the U.S. and at the international level. Some major companies have adopted

internal variations in the way that they interpret and apply the standards. It is believed that this practice will result in interoperability problems in the near future. The standards effort must be international, involving multiple government standards organizations.

Solution 1: International integration of the GD&T standards.

In addition to the issues and solutions presented above, the product definition group provided the following additional observations and comments on the current state that do not rise to the level of major issues.

- If you can't associate GD&T data with part features you can't control the inspection plan.
- Companies can shy away from BIG PROJECTS – don't tackle all issues at once – focus on smaller issues in phases.
- The scope of CAD companies focus is expanding beyond just CAD – standards don't match their business case. We need to know their goals better.
- Vendors currently expend great effort in multiple directions trying to integrate – there are too many directions to follow all.
- Can a standard format cause loss of proprietary capability data? – If so, this may give vendors less incentive to improve capabilities.
- STEP uses a file-based approach, which often results in vendors buying tools that manipulate the files through an API. AIMS, for example, is a direct API approach where, at this time, the user does not manipulate external files.
- Is the IMIS forum considering only open, non-proprietary specifications / standards? Is there a path for migrating "open proprietary" to "open non-proprietary"?
- What are other issues in dealing with older, "legacy" systems? For example, it is impractical or even impossible to upgrade them, and it is difficult to discard working systems and their data.
- What could be the role in standards for specifications or tools based on the model of "open source code" tools and applications?
- The use of standards doesn't necessarily reduce costs of buying new software licenses. A standard will reduce this cost if the number of different products used for data translation can be reduced.
- How did the WEPROM (Werkergerechte prozesskettenorientierte Messtechnik Softwarekonzept[3]) effort get extensive user involvement? How did the I++ effort get so much user involvement?
- There will always be costs of keeping products up with revisions in specifications.
- Out of scope issue: How can well-integrated data be used:
    - To detect errors in inspection plans?
    - To detect errors in equipment function?
    - To detect errors in application software?

[3] Precision process-chain-oriented metrology software concept

- To detect errors in inspection programs?

Future Vision for Product Definition

- Multi-process manufacturing will have traceable nominal feature data.
- Internet posting of part design data for bidding by contractors.
- The information needed to develop manufacturing sequences, fixturing plans, inspection plans, and manufacturing programs, can be extracted automatically from the product design data.
- All standards will be harmonized.
- Existing standards will be extensible, partly through good modularization.
- There will be organization of complete product data across the product lifecycle.
- No data left behind - the definitions of data interfaces will be complete and all-important data will be conveyed effortlessly.
- Open interface specifications are extensible.
- One can choose a product vendor and not lose interoperability with my other components.
- Data will be exchanged without use of industry agreements (vendor-to-vendor handshake).
- Data can be archived long term without the need to preserve the applications that generated them.
- There will be industry-wide agreement on data formats - “everybody plays” in the standards arena.
- Interface specifications will be stable, and new needs will be addressed quickly.
- Generate DMIS automatically using standard data.

3.2. Technology Plan for Inspection Process Definition

Participants in the inspection process definition group included Ray Admire (Lockheed Martin MFC), Kalyan Bhamidi (Caterpillar), Curtis Brown (Honeywell FM&T), Robert Callaghan (Independent Quality Labs), Jess Crusey (Northrop Grumman), Murray Desnoyer (Origin International), Rob Edgeworth (Intel), Cory Leland (Deere), Larry Maggiano (Mitutoyo), Carol Malone (Macomb Community College), Dave Marlow, John Michaloski (NIST, session scribe), Helen Guixiu Oiao (API), Ken Sheehan (Quality Vision International), Andy Smith (Renishaw), Doug Sponseller (Timken), Tim Taylor (GE Aviation), Al Wavering (NIST, session facilitator), Art Whistler (Helmel), and John Wootton (LK).

The Inspection Process Definition breakout group created the detailed activity model shown in Figure 7. From the perspective of dimensional metrology, the most important functions of the *inspection process definition* activity are:

- To extract or accept as input from the product definition model all the information necessary to generate a complete inspection process plan called the *macro process plan*.
- To generate a device-independent *micro process plan* containing the necessary information to execute the part inspection process.

The activity diagram can be viewed as a high-level overview of all the functions that must be supported in order to generate an inspection process plan for use by the downstream execution of the part inspection process. Some of these functions are performed intelligently by today's software, while others require manual intervention. Clearly there are many interoperability issues between the *product definition* activity and the *inspection process definition* activity. Within the process definition activity, there are a host of interoperability issues if the process plan is expected to provide device-independent support for the myriad inspection devices that are available for process execution. The question of how the inspection process activity makes the inspection process plan available to the downstream executor of the inspection process is also an interoperability issue.

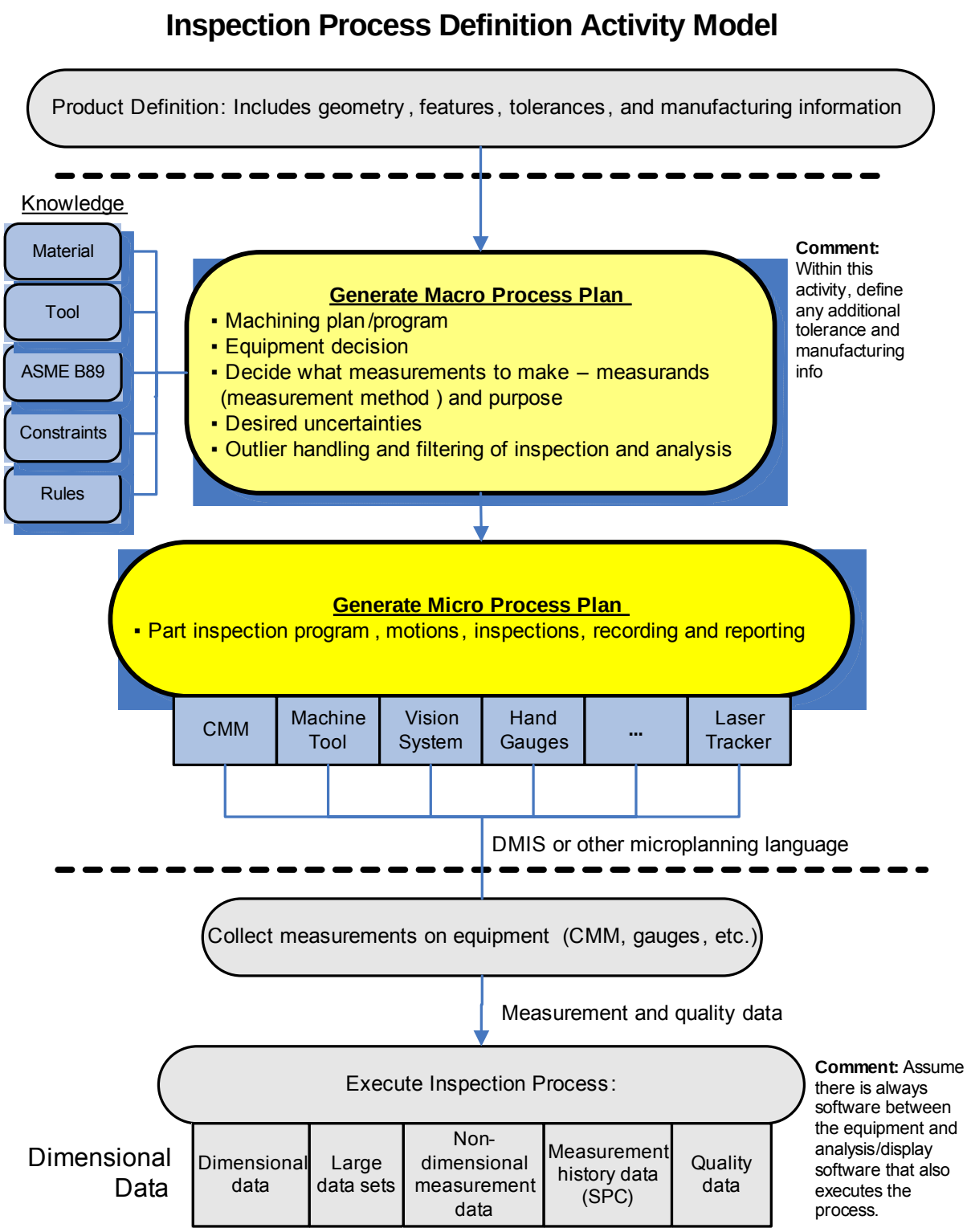

Figure 7. The activity model for inspection process definition summarizes the various functions that must be supported to design and generate a complete inspection plan.

Current-State Assessment for Inspection Process Definition

In evaluating the current state of the *inspection process definition* activity, the group identified a number of key findings, many of which could be translated into interoperability issues.

In today's manufacturing environment, dimensional metrology includes more than just inspecting the part for conformance to the key dimensions on a drawing. Measurements are also used:

- To provide feedback needed for control of the manufacturing process.
- To provide statistical data for the evaluation of conformance to tolerances at the feature level.
- To provide manufacturability feedback to the product definition (design and development) activity.
- To provide calibration and tolerance-centering for upstream manufacturing processes.

The group noted that there is a lack of information in digital format to define measuring system capabilities in terms of performance, measurement uncertainty, and configuration. Tolerance definitions are often incomplete, ambiguous, inaccurate (or wrong). There is no change capability or associativity back into the CAD product design model, meaning that there seems to be no way to update/improve a product design when design errors are discovered in Process Definition. There is also no standard digital format for transmitting knowledge-based manufacturing and inspection rules. It is now done with a lot of "cut and paste" activity. In today's inspection process definition tools, there is currently a lack of DMIS compatibility, and a lack of interactive and/or static conformance classes, meaning that there are multiple proprietary data formats and a lack of tools allowing user access to the data.

Interoperability Issues for Inspection Process Definition

Table 2 summarizes the top interoperability issues identified by the inspection process definition group. Following the table, recommended high-level solutions and (where available) more specific actions are presented for each issue.

Table 2. The top metrology interoperability issues, as identified by the inspection process definition group.

Top Inspection Process Definition Issues
The lack of comprehensive non-shape information available from the product definition model – CAD Tolerance Data, material properties, optical properties, etc.
The lack of a standard mechanism to capture and exchange knowledge – including methods, practices, and rules.
The lack of resource definition from the product definition model or elsewhere – such as inspection equipment capability, capacity, available configuration, performance, measurement uncertainty, etc.
Does DMIS support all measuring devices?
The macro-to-multiple-micro planning interface is not well defined.

Issue 1: There is a lack of comprehensive non-shape information available from the product definition model – geometric and dimensional tolerance data, datum reference frames, material properties, optical properties, etc. This issue is considered a "showstopper", and must be solved if interoperability is to be realized between product definition models, inspection process definition and planning products, and downstream processes.

Solution 1: Evaluate GD&T in AP203 2nd Edition – also consider material properties, surface finish, etc.

Action: Assess AP203 2nd Edition for its scope and completeness for representing tolerances and other measurement criteria and report discrepancies to NIST.

Solution 2: Put GD&T definition in a derivative environment other than CAD and verify the schema.

Action: Put plug-ins available to extract information into AP203 (Edition 2)

Solution 3: Push CAD vendors to supply associative GD&T (beyond annotations) as a part of their model.

Solution 4: Educate users to prevent the use and acceptance of incomplete, inaccurate, wrong, or ambiguous GD&T information.

Issue 2: There is a lack of a standard mechanism to capture and exchange knowledge – including measurement methods, practices, and rules.

Solution 1: Define an extensible interface standard for capture and exchange rules.

Issue 3: There is a lack of resource definition from the product definition model or elsewhere – such as measurement equipment capability, capacity, available configuration, performance, measurement uncertainty, sensors, fixtures, rotary tables, etc.

Solution 1: Assess various measuring system capabilities & resource configuration information.

Action 1: Assess the ASME B5.59 series, and explore whether the ASME B5.59 applies to coordinate measuring machines.[4]

Action 2: Assess DMIS as it relates to the definition of machine configuration.

Action 3: Assess the work done by I++ and Renishaw regarding machine configuration using extensible markup language (XML).

Action 4: Assess the content of ISO 10360-1 as it relates to machine type and definitions.

Solution 2: Provide a better sensor model that is more suitable for plug and play implementations.

Action 1: Produce a laundry list of available sensor models.

Solution 3: Define a common standard method of communicating resource information.

Action 1: Collate various resource equipment standards to revise standards.

Issue 4: Does DMIS support all measuring devices?

Solution 1: Verify DMIS against various measuring devices

Action 1: Gap analysis for vision, laser tracker, on-machine CNC probing, etc.

[4] The authors of this document (NIST and IMTI) do not have knowledge of the standard (ASME B5.59) referred to here.

Action 2: Determine whether or not DMIS is sufficient to span across I++ functionality.

Issue 5: The macro-to-multiple-micro planning interface is not well defined.

Solution 1: Improve the definition of the interface to provide additional and more complete support of multiple measurement devices**.**

Action 1: Evaluate candidate solutions (currently DMIS). If DMIS is not the answer, create a different solution or enhance DMIS.

Cultural Issues – The process definition group identified the following "cultural" issues that affect interoperability, many of which are crosscutting issues.

- Lack of CAD vendor interest in changing the status quo.
- How to handle legacy parts that don't have CAD models.
- Culture change necessary to align design/manufacturing/measurement functions.
- How comprehensive should the scope of our efforts be?
- Are we addressing the needs of small manufacturers?
- Education and lack of knowledge.
- Improving the understandability of standards and units, and removing ambiguities.

Future Vision for Inspection Process Definition

VISION STATEMENT FOR INSPECTION PROCESS DEFINITION

The *inspection process definition* activity can interact seamlessly with *product definition information* coming from any CAD system, using this information to provide unambiguous instructions that can run on any CMM/Measuring Equipment appropriate to measurement requirements.

The group developed the above vision state for inspection process definition, and provided the following list of elements for their vision:

- Represent results back to CAD, since there is currently no automatic, integrated (non-manual) path from reporting to CAD
- The knowledge base used by the entire metrology process should be accessible and extensible – not something that is invisible or lost in a black box.
- Generation of the inspection process/program will be automated.
- A standard graphical representation of part and feature deviations will be adopted.
- Raw data will be stored in a lossless, compressed format that will be retained throughout the manufacturing life cycle.
- Keep all data all the time, forever.
- Results feedback into process planning at different timescales to optimize measurements, since there is currently no automatic, integrated (only manual) path from reporting to process planning
- Link everything back into enterprise content management – beyond Product Data Management (PDM).
- Cost predictive tool – design for manufacturability, tolerance for inspectability (ABC, history based)

Roadmap Chart for the Process Definition Breakout Group

The Process Definition breakout group identified five significant issues affecting metrology interoperability as it relates to product definition. This is an excellent start for a roadmap diagram (shown in Table 1Table 3). The remaining information (dependencies, cost, timelines, duration, and metrics for success) can be added to the diagram at a later date.

Table 3. A roadmap for the Process Definition Breakout Group. (The timeline, cost, benefit, and performance metrics will be populated in a subsequent work session.)

Process Definition - Actions Level Roadmap

WBS	KEY Issue Solution Action	PRI	Timeline FY '07 FY '08 FY '09 FY '10 FY '11 FY '12 FY '13 FY '14 FY '15 FY '16 FY '17
1	Lack of complete product definition (non-shape information missing)		
1.1	Evaluate non-shape (e.g. GD&T) in AP203e2 - Also consider material properties, surface finish, etc.	H	
1.1.1	Assess AP203 2nd Edition for its scope and completeness for representing tolerances and other measurement criteria and report discrepancies to NIST.	H	(To be determined)
1.2	Put GD&T in a derivative environment other than CAD and verify the schema.	H	(To be determined)
1.2.1	Put plug-ins available to extract information into AP203 (Edition 2)	H	(To be determined)
1.3	Push CAD vendors to supply associative GD&T (beyond annotations) as a part of their model.	H	(To be determined)
1.4	Educate users to prevent the use and acceptance of incomplete, inaccurate, wrong, or ambiguous GD&T information.	H	(To be determined)
2	No standard for measurement knowledge		
2.1	Define extensible interface standard to convey measuring related knowledge	H	
3	Lack of Exchange of Resource Definition		
3.1	Assess various measuring system capabilities and resource configuration information.	H	(To be determined)
3.1.1	Assess the ASME B5.59 series, and explore whether the ASME B5.59 applies to coordinate measuring machines.	H	(To be determined)
3.1.2	Assess DMIS as it relates to the definition of machine configuration.	H	(To be determined)
3.1.3	Assess the work done by I++ and Renishaw regarding machine configuration using extensible markup language (XML).	H	(To be determined)
3.1.4	Assess the content of ISO 10360-1 as it relates to machine type and definitions.	H	(To be determined)
3.2	Provide a better sensor model that is more suitable for plug and play implementations.	H	(To be determined)
3.2.1	Produce a laundry list of available sensor models.		(To be determined)
3.3	Define a common standard method of communicating resource information.	H	(To be determined)
3.3.1	Collate various resource equipment standards to revise standards.		(To be determined)
4	DMIS support for all CNC measuring device types.		
4.1	Verify DMIS against various measuring devices.	M	(To be determined)
4.1.1	Gap analysis for vision, laser tracker, on-machine CNC probing, etc.	H	(To be determined)
4.1.2	Determine whether or not DMIS is sufficient to span across I++ functionality.	H	(To be determined)
5	Macro-to-multiple-micro planning interface is not well defined.		
5.1	Define content of the interface.	M	(To be determined)
5.1.1	Evaluate candidate solutions, if it is DMIS. If not create one or enhance DMIS.		

3.3. Technology Plan for Inspection Process Execution

Participants in the inspection process execution group included Paul Clausen (NDI), Alberto Griffa (Geomagic), Zev Handler (Hexagon/Wilcox), Ronald Hicks (Northrop Grumman Newport News), Kam Lau (API), Lutz Karras (Zeiss), Keith Mills (Xspect Solutions), Nick Moffitt (Verisurf), Josef Resch (Zeiss), Etienne Rossignon (Delcam), Bailey Squier (DMSC, Inc.), Hui-Min Huang (session scribe), and Fred Proctor (NIST, session facilitator).

The *inspection process execution* breakout group created the detailed activity model shown in Figure 8. From a very high-level perspective, the most important functions of the inspection process execution activity are:

- To accept input from the inspection process plan and use the input to provide unambiguous instructions to a variety of inspection equipment.
- To use the inspection equipment to inspect a component.
- To save the inspection results.
- To provide output to the analysis and reporting activity.

As simple as this makes the process sound, interactivity issues abound – both between the *inspection process definition* activity and the *inspection process execution* activity, and within the inspection process execution activity. Not only are there a huge number of different types of inspection equipment that must be supported, there are an almost limitless number of ways in which a complex part can be inspected. The goal is to achieve interoperability with a high degree of automation and a minimum amount of manual intervention.

If the inspection process plan does not result in a complete and unambiguous inspection program, then corrective action must be taken before the inspection process can proceed. If the inspection program is not compatible with the available inspection equipment, then there are a multitude of options available for addressing the interoperability problem. Unfortunately, none of them are inexpensive, short-term solutions. Potential options:

- Translate the inspection program into format that is compatible with the available equipment.
- Purchase compatible inspection execution software and obtain the additional training needed to use the software.
- Negotiate with the process planning software vendor to make the needed changes in the software.
- Replace or augment existing inspection equipment with new equipment that is compatible with the process planning software.
- Demand standards-compliant dimensional metrology software (or consider a single-vendor solution if one is available).

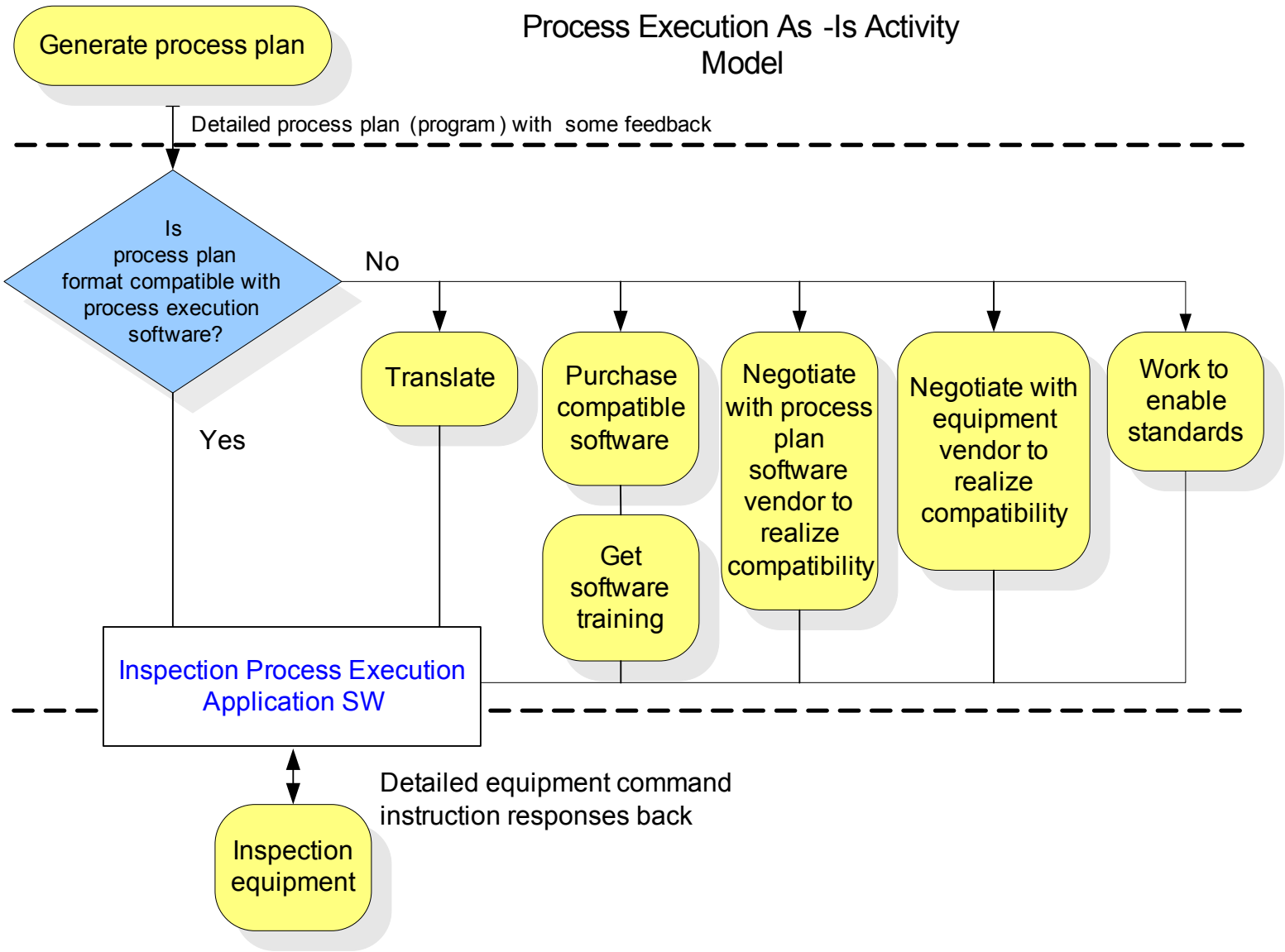

Figure 8. The *inspection process execution* as-is activity diagram focuses on interoperability issues with the *inspection process definition*/planning activity.

The issue of standards – whether they are *de facto* or official – became the focal point for discussion in the inspection process execution group. There are two widely used standards – one of which has been formalized as an official ANSI and ISO standard – that attempt to address dimensional inspection interoperability issues. These are the *Dimensional Measuring Interface Standard* (DMIS) – more specifically DMIS Part 2, and I++ DME, a specification for dimensional measuring equipment information exchange started by several European automakers and measuring equipment vendors. Only the DMISequip portion of DMIS Part 2 overlaps with I++ DME. Even though DMISequip is part of an ISO standard, there are no known product implementations, whereas the are many product implementations of I++ DME, so I++ DME can properly be viewed as the *de facto* standard.

The IMIS Process Execution group identified two issues of critical importance relating to the I++ DME specification:

1) I++ DME should be released to some appropriate and accredited standards body, so that anyone interested can provide input toward changes and additions to the standard (specification).

2) The I++ group should give sufficient assurances that there will be no requirement, either now or in the future, that royalties be paid by any individual or company solely for using the I++ DME language in their metrology products.

The new Dimensional Metrology Standards Consortium (DMSC) standards body was proposed by some members of the group as the place for such standardization, because they have ANSI and ISO accreditation, strong metrology expertise, and ISO “fast track” capability. It was also proposed that I++ DME become part of an expanded DMIS standard. No one in the group voiced opposition to these two proposals at IMIS.

Current-State Assessment for Inspection Process Execution

Interoperability issues that affect inspection process execution are arguably more important in large, enterprise-level corporations such as those in the automotive and aerospace industries than they are in small companies with few in-house metrology resources. At the enterprise level, a single-vendor solution becomes impractical if not impossible. The need for interoperable software products that executes the manufacturing and inspection process in a highly automated and equipment-independent fashion becomes critical to an enterprise-level corporation’s very survival. Even at the job-shop level, a single-vendor solution can restrict the ability to choose best-in-class equipment for a particular application or may require redundant training on new software to enable best-in-class equipment choices.

Interoperability Issues for Inspection Process Execution

Table 4 summarizes the top interoperability issues identified by the inspection process execution group. Following the table, recommended high-level solutions and (where available) more specific actions are presented for each issue.

Table 4. The top five metrology interoperability issues, as identified by the inspection process execution group.

Top Inspection Process Execution Issues
I++ DME isn't a formal standard.
Overlap between I++ DME and DMIS Part 2 – dueling standards.
I++ DME needs to be extended to handle more equipment, sensors, environment.
A formal I++ DME framework is needed.
Implementation barriers need to be reduced.

Issue 1: I++ DME is not a formal standard.

Solution 1: A formal standard is needed for I++DME.

Priority = High.
Duration = 1 year.
Start = now.
Metric for success = Public documents produced.
Benefit = Increased acceptance.
Cost = $50K.

Actions:

1. Resolve the intellectual property and other legal issues that are barriers to I++ becoming a standard.
2. Ensure that future roadmap of I++DME includes the request and wishes of the user community.
3. Move to standardize the current I++DME 1.5 as standard version 1.0.
4. Prepare drafts with support for portable arms, scanners, trackers, vision sensors, etc.

Issue 2: There is overlap between I++ DME and DMIS, Part 2 – dueling standards.

Solution 1: Resolve the I++DME versus DMIS, Part 2 issue.

Priority = High.
Duration = 1 year.
Start = now.
Metric for success = DMIS, Part 2 eliminated (or possibly just the DMISequip module).

Benefit = Increased acceptance.
Cost = $50K.

Actions:

1. Assess activities of I++DME and DMIS, Part 2.
2. Participants in the International Metrology Interoperability Summit will work with the Dimensional Metrology Standards Committee (DMSC) to resolve the overlap between I++ and DMIS, Part 2, so that we have a single solution.

Issue 3: I++ DME needs to be extended [to handle more equipment, sensors, environment].

Solution 1: Extend I++DME.

Priority = High.
Duration = 2 years.
Start = now.
Metric for success =
– Phase 1: I++DME supports trackers, arms
– Other phases: vision, environment, enhancements (>2 years)
Benefit = Increased customer base.
Cost = ?.

Issue 4: A formal I++DME framework is needed.

Solution 1: Establish a formal standards development framework for I++ DME

Priority = Medium.
Duration = 1 year.
Start = 1 year after the IP issues are resolved.
Metric for success = Processes are documented and accepted.
Benefits:

– Ensure long-term survivability of the group's activities
– Preserve participants' investments
– Foster the promotion and education process

Cost = ?

Solution 2: Support, coordinate, and expand testing activities; e.g., the NIST test bed NIST test suite, and public interoperability tests.

Issue 5: Implementation barriers need to be reduced.

Solution 1: Remove barriers to implementation.

Priority = Medium.
Duration = 3 years.
Start = Now.
Metric for success =

– Proof-of-concept for new equipment.
– Equipment classes defined.
– Conformance tests available.

Benefits: Accelerated development and deployment.

Action1: Establish centralized I++DME site (www.iplusplussdme.org, www.ia-cmm.org, www.nist.gov?

Action 2: Develop open source reference implementation and conformance tests.

Action 3: Consider adding equipment classes to I++DME.

Action 4: Foster training for developers and implementers.

Action 5: Undertake pilot projects.

The group also identified the following emerging issues:

Emerging Issue1: Need to reduce the entry cost for I++ DME implementation; I++ is a moving target.

Solution 1: Produce reference implementation/development kits, training, centralized information site.

Emerging Issue 2: Intellectual property issues.

Solution l: Utilize a fast track standardization process such as DMSC (Representative group), since DMSC has a "fast track" option within ISO.

Emerging Issue 3: Collision avoidance volume definitions are too coarse.

Solution 1: Downloadable library of precise sensor shape geometries.

Emerging Issue 4: Users do not have ready I++ products. I++ is in a developmental status (moving target), creating problem for vendors

Emerging Issue 5: Vendors have to maintain too many software versions; they are wanting to learn about I++ and how they can benefit.

Solution 1: Centralized I++ information site, a pilot project to explore issues, perhaps separate groups to deal with fixed CMM (established) and portable (emerging) measurement equipment technologies. (The software could be quite different.)

Solution 2: Portable CMM vendors need to study the I++ DME specification and make recommendations to the I++ DME group as to what needs to be expanded in I++ DME to make it useful for portables. Even better is to also run a pilot/implementation to uncover even more details.

Action: Josef Resch will recommend this to the I++ DME consortium.

Emerging Issue 5: Employ three parts on DMIS relevant to Interoperability – the DMIS program file, the DMIS interpreter and its interface to the server via I++DME, The executor and its interface to reporting and analysis via DML.

Solution: Use the Dimensional Metrology Standards Consortium (DMSC, Inc.).

Future Vision for Inspection Process Execution

VISION STATEMENT FOR INSPECTION PROCESS EXECUTION

PROVIDE A SINGLE PLUG AND PLAY PROTOCOL (STANDARD) FOR DATA EXCHANGE BETWEEN APPLICATION SOFTWARE AND DIMENSIONAL MEASURING EQUIPMENT, REGARDLESS OF VENDOR. THIS PROTOCOL SHOULD APPLY TO ALL TYPES OF DIMENSIONAL MEASURING EQUIPMENT AND ALL TYPES OF SENSOR TECHNOLOGY.

3.4. Technology Plan for Analysis and Reporting of Quality Data

Participants in the *analysis and reporting of quality data* group included Robert Brown (Mitutoyo America), Joe Falco (NIST, session scribe), Alberto Griffa (Geomagic), Rich Knebel (Zeiss), Joe Schafer (UGS), Bob Stone (Origin International), Kim Summerhays (MetroSage), Ted Vorburger (NIST, session facilitator), Per-Johan Wahlborg (IVF), and Fredrik Wandeback (IVF).

Current-State Assessment for Analysis and Reporting of Quality Data

The *analysis and reporting* breakout group created the detailed current state activity model shown in Figure 9. As can be seen from the diagram, the most important functions of the analysis and reporting activity are to receive input from the *inspection process execution* and the *product definition* activities, to analyze the part inspection data in terms of product definition requirements, and to perform a statistical analysis of the inspection results and present them in the form of a statistical process control report. The model provides an overview of the complete dimensional metrology process from the perspective of the *analysis and reporting* group. Note that boundaries are shown around each of the four sub-processes. Within each sub-process, there are interoperability issues brought about by incompatible hardware and software, a lack of formal standards (or conflicting standards), and other factors. Although the issues are not specifically identified and described, the diagram also indicates that interoperability issues exist at the boundary between the *product definition* and the *inspection process definition* sub-processes; between the *product definition* and the *analysis and reporting* sub-processes, and between the *process definition* and the *process execution* sub-processes.

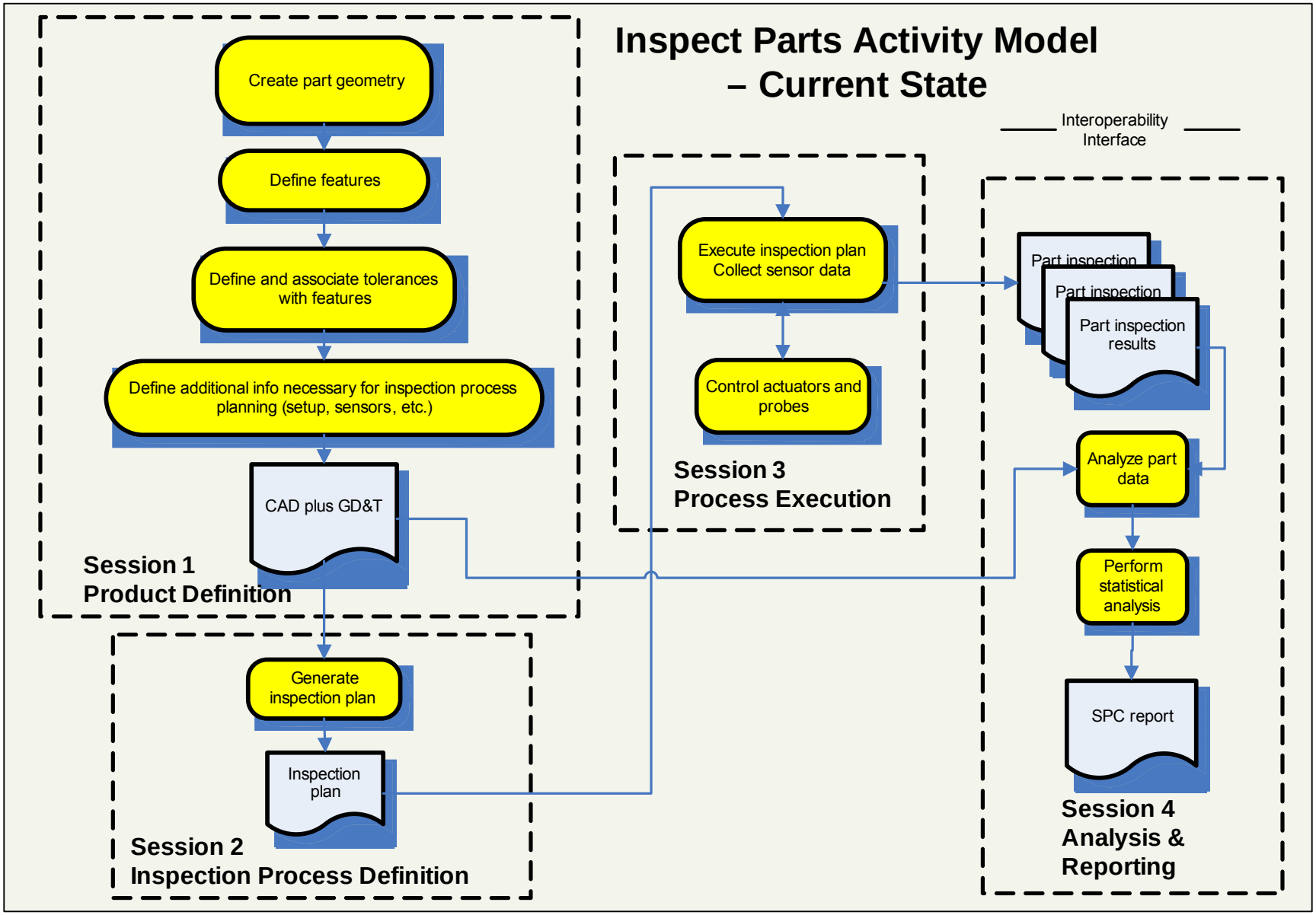

Figure 9. This activity model diagram depicts the *current state* of the dimensional metrology process, and identifies the major interoperability issues affecting the four areas addressed during the interoperability workshop.

Working from the current state activity model, the analysis and reporting group identified the following key functions, deficiencies, cultural and technological barriers, and emerging best practices for the analysis and reporting activity. This information is presented in Table 5.

Table 5. Key function, deficiencies, barriers, and emerging best practices were extracted from the *analysis and reporting* activity model.

Key Functions	Deficiencies – Where Does it Hurt? How Badly?	Barriers – What's in the Way?	Emerging Best Practices
• Generate Sensor Data	• No attribute data • Cannot handle large data sets - performance • Non-uniform implementation of standards • Lack of simplicity of standards	• Multiple standards / specifications (i.e., AIMS, QS-stat ASCII, AP219, DMIS, DML (Dimensional Markup Language), I++, …)	• DML • DMIS • AP219
• Report to Business Systems	• Interfacing quality data to business Enterprise Resource Planning (ERP)	• We don't understand what they need and they don't understand what they can get.	• OAGI – Open Application Group • UBL - Unified Business Language
• Do Measurement Planning	• Lack of knowledge about appropriate inspection technique (i.e., tolerances, algorithm sampling plan)		• Inspection Techniques Specification • Automotive measurement practices (AP/QP) • Mil Specs (Z1-3 …)
• Traceability Data	• Non-uniform implementation of standards • Insufficient links between traceability and inspection data	• Multiple standards / specifications / practices	• AIAG subcommittee MEQM • AP238 traceability component • DMIS
• Perform Statistical Analysis	• Lack of statistical standardization • Lack of knowledge	• Multiple standards / specifications • Not high on customers perceived list of priorities	• ASQ • AIAG • CNOMO • GM • Juran/Demming • ISO 16949 (QS 9000) • Boeing AS 9100
• Evolve Manufacturing Process	• No standard methodology for adjusting a process • Unambiguously communicating proposed process change	• No standard machine controller interface • Human link	• Renishaw • M&G Codes • AP238 (STEP NC) • Gleasonworks Feedback Process (12 adjustments)

In addition to the key functions listed in Table 5, the analysis and reporting group generated the following notes that were helpful in identifying key issues. The notes as captured by the group's scribe are included here for the sake of completeness:

- Storage is also an issue
- Start diagram is vendor specific for standards; effort needs to be neutral.
- IP – Profit for producer
- Different outputs between products – precision, parameters, definitions, algorithms, algorithms, uncertainties, standard deviation. Ex. PPK, CPK Quality specs. – example Boeing's AS 19000

- Use case/ flow of event examples are available AIAG perspective
- There should be a unification process as far as SPC
- Map process as it is from A to B. Steps from measure to report.
- Single measurement – integration of measurements (i.e., different physical locations). Is it a single part, multiple parts….
- Quality data must be complete
    - What production machine produced a bad feature? (Need birth certificate, traceability) to machine. The environment of the part as it is being manufactured.
    - Data Type 1-characteristics, 2-feature data, 3-raw data, 4-data stream
- Data reduction without losing critical information
- Data analysis planning is important before the inspection process design.
  There is lots of info from design – tolerances but need more information on how to measure. No backflow of this information in the planning process
- Different data purposes: reverse engineering, process characterization, part qualification.
- Evolve inspection analysis and planning procedures with product and process development.
- DML Dimensional Data – Quality data must also include attributes such as conformance, non conformance (i.e., surface defects) data
- Need feedback to manufacturing process.
- Current state of DML
- Quality data standards are evolving now (i.e., QML)
- Optical data – how to describe
- Quality data must interface with business systems
- MES- Manufacturing Execution System
- ERP - Enterprise Resource Planning

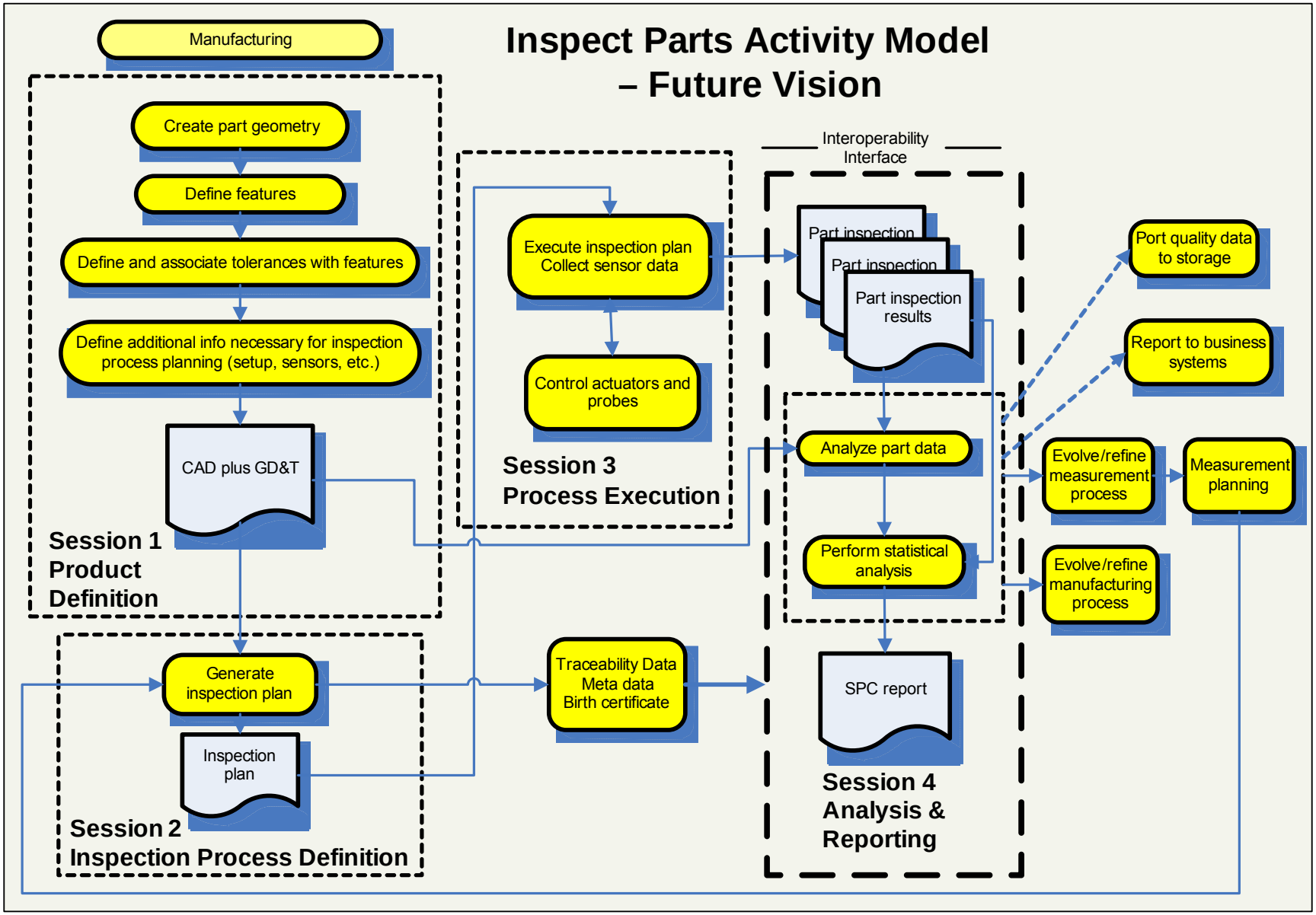

Figure 10. This activity model diagram depicts a future vision for the dimensional metrology process, and identifies the major interoperability issues affecting the four areas.

Interoperability Issues for Analysis and Reporting of Quality Data

The top interoperability issues and solutions defined by the analysis and reporting group are shown in Table 6.

Table 6. Top *analysis and reporting* dimensional metrology interoperability issues.

Top Analysis and Reporting Issues and Solutions	
Lack of uniform data model for the single part report (cross-cutting issue)	**Provide unified data models for single part inspection measurement results**
Lack of uniform data model for quality study summary reports with traceability (cross-cutting issue)	**Develop unified data model**
Bandwidth and storage limitations (data overload)	**Handle large data and provide acceptable performance**
Synchronization and correlation of all data for each measurand (primarily traceability) (cross-cutting issue)	**Augment data flow models to uniformly integrate data from different sources into single part and summary report data models**
Lack of feedback of study data for manufacturing	**Augment data model for feedback to manufacturing**
Lack of consistency of statistical calculation methods and definitions	**Capture and identify best practices and unify into a single standard**
Lack of feedback of study data for measurement planning	**Develop a methodology to change the measurement and sampling plan based on measurement results**
Planning for report formatting (standardization of report templates)	
Legacy systems are too dumb and costly to update (cross-cutting issue)	
Proprietary business models (cross-cutting issue)	

Future Vision for Analysis and Reporting of Quality Data

Figure 10 is similar to Figure 9 except that it shows a *future vision* activity model for the analysis and reporting process. In this future vision, an attempt has been made to identify an activity interface boundary that clearly identifies the interoperability issues that affect the analysis and reporting group. The vision statement for *analysis and reporting* is shown below.

VISION STATEMENT FOR ANALYSIS AND REPORTING OF QUALITY DATA

- **A unified data model (integrated resources) with a common understanding of the definitions in the data model.**
- **Portability is a requirement.**
- **Accessibility to all data in an easy way without duplication (customer perspective)**

The following vision characteristics were also reported by the group to address the issues previously identified:

Characteristics of the Vision for “Report to Business Systems”

- Automatic delivery of data to the semantics of a business systems

Characteristics of the Vision for “Measurement Planning”

- An educated work force
- Continuous improvement of the measurement process
- Automatic delivery of data to the semantics of a measurement planning system

Characteristics of the Vision for “Traceability Data”

- Traceability data is only entered once or captured automatically
- Common terminology
- Easy ad-hoc filtering

Characteristics of the Vision for “Perform Statistical Analysis”

- More visible role for uncertainty
- Uniform calculation methods with a reference to the calculation method used
- Intuitive results analysis with the ability to drill down

Characteristics of the Vision for “Evolve Manufacturing Process”

- Automatic and easy manual adjustments of manufacturing equipment
- Ensure that analysis and reporting standards efforts are coordinated with the standards efforts of manufacturing planning and execution

Roadmap Chart for Analysis and Reporting of Quality Data

A roadmap chart is shown in Table 7 for the Analysis and Reporting of Quality Data breakout group. The group identified 10 important issues affecting metrology interoperability and devised high-level solutions and lower-level action statements for seven of the issues. This is an excellent start for a roadmap diagram, and the remaining information (dependencies, cost, timeline, duration, metrics for success) can be added at a later date.

Table 7. A roadmap for the Analysis and Reporting of Quality Data Breakout Group. (The timeline, cost, benefit, and performance metrics will be populated in a subsequent work session.)

Analysis and Reporting of Quality Data - Actions Level Roadmap			
WBS	KEY Issue Solution Action	PRI	Timeline FY '07 FY '08 FY '09 FY '10 FY '11 FY '12 FY '13 FY '14 FY '15 FY '16 FY '17
1	Lack of uniform data model for the single part report.		
1.1	Provide unified data models for single part inspection measurement results	H	(To be determined)
1.1.1	Investigate ASME B.5.59.	H	(To be determined)
1.1.2	Evaluate and choose between: Improve DML, Improve DMO, Improve STEP models, Develop new data model from scratch	H	(To be determined)
2	Lack of uniform data model for quality study summary reports with traceability.		
2.1	Develop unified data model.	H	(To be determined)
2.1.1	Investigate ASME B.5.59.	H	(To be determined)
2.1.2	Evaluate and choose between: Improve STEP models, Realize AIAG MIPT MEQM data model, Improve and gring to the public domain QML.	H	(To be determined)
3	Bandwidth and storage limitations (data overload).		
3.1	Handle large data and provide acceptable performance.	H	(To be determined)
3.1.1	Be rigorous in defining all use cases	H	(To be determined)
3.1.2	Develop timing diagrams and use threading.	H	(To be determined)
3.1.3	Further optimization of data models.	H	(To be determined)
3.1.4	Maximize throughput of data pipe (minimum and recommended hardware requirements).	H	(To be determined)
4	Synchronization and correlation of all data for each measurand (primarily traceability)		
4.1	Augment data flow models to uniformly integrate data from different sources into single part and summary report data models.	H	(To be determined)
5	Lack of feedback of study data for manufacturing.		
5.1	Augment data model for feedback to manufacturing.	M	(To be determined)
5.1.1	Investigate existing manufacturing AP's.	H	(To be determined)
5.1.2	Develop data model for minimum requirements for traceability of a measured characteristic to an operation.	H	(To be determined)
6	Lack of consistency of statistical calculation methods and definitions.		
6.1	Capture and identify best practices and unify into a single standard.	M	(To be determined)
6.1.1	Identify existing standards and consolidate.	H	(To be determined)
6.1.2	Provide a test suite (NIST).	H	(To be determined)
6.1.3	Work with NIST to provide a certification process.		(To be determined)
7	Lack of feedback of study data for measurement planning.		
7.1	Develop a methodology to change the measurement and sampling plan based on measurement results.	M	(To be determined)
7.1.1	Identify current best practices.	H	(To be determined)
7.1.2	Assess impact of GM patent application	H	(To be determined)
7.1.3	Need academic involvement.		(To be determined)
7.1.4	Need a champion to carry the message (Crosby or Wheeler)		(To be determined)
8	Planning for report formatting (standardization of report templates).		
9	Legacy systems are too dumb and costly to update.		
10	Proprietary business models.		

3.5. Cross-Cutting Issues (Interoperability issues that clearly encompass more than one area)

Crosscutting Issue 1– The Product Definition group identified one important crosscutting issue that currently has an adverse effect on every aspect of the dimensional metrology process: **There are currently no "consensus" approaches to the interconnection of components/systems. The "big picture" needs to be defined before unified efforts can be developed to solve this important problem.** There is no shared vision between vendors and users for interoperability. There are many cultural issues that prevent a shared vision from being adopted:

- Barriers to the widespread adoption of standards by equipment and software vendors:
    - Lack of a shared vision – The multitude of competing and conflicting standards and practices are barriers to the development of a shared vision for interconnection.
    - No standards are in place, or no conformance tests exist to verify compliance to the standard.
    - There are few or no implementations of the standard
- There is a lack of consensus on whether the exclusive use of open-source, non-proprietary, standards-based hardware and software is a more effective option than single-supplier network, proprietary hardware and software.
- Vendors feel compelled by economic necessity to protect their proprietary information in order to offer improved products that are differentiated from those of their competitors. From their perspective, there is no economic incentive to offering open-source, non-proprietary products; and there is little economic incentive to offering standards-based products.
- Standards tend to lag behind the development of new product features. One way to minimize this time lag is to ensure that both vendors and end users actively participate in the development and revision of standards on a continuous basis. However, this is a costly endeavor.

Solution for Crosscutting Issue 1: The product definition group proposed a high-level solution that could foster the development of the needed shared vision for interoperability. The group suggested that a first step would be to gather information from all the major metrology interoperability stakeholders to determine their business and organizational objectives. Stakeholders include:

- CAD, metrology, and Product Lifecycle Management (PLM) vendors.
- End users, users consortia (e.g. AIAG), and suppliers
- Government and standards organizations (both domestic and international)

Once the stakeholder objectives are better understood, a concerted effort must be made to find alignments of these objectives that result in a win-win situation for all stakeholders. Vendors must be able to protect and improve their proprietary information but still conform to standards. A method must be found of ensuring continuous stakeholder involvement in the timely update of interoperability standards.

The lag of standards behind new product features is mitigated by the fact that if one is committed to a single supplier network, one cannot easily integrate that new feature if the feature comes from a product outside the single supplier network!

The perception that vendors will lose product differentiation is at least partly false, as can be shown easily through an example. Clearly, PC printers are now interoperable with PC computers: only a minimal effort is required to install and begin using a new printer from any manufacturer. However, printing quality and price vary widely, allowing the customer many choices with regard to quality, durability, efficiency, cost, etc.

Standards are not typically in the best interests of the vendor, particularly for the large vendor. Having users beholden to the products of a single vendor virtually eliminates competition and invites a more profitable (to the vendor) product pricing structure. Smaller vendors may be interested in standards, but small vendors want to become large vendors, so the interest may be short-lived.

End user support is the secret to the success of most if not all standards and interoperability solutions. If enough users demand an open, non-proprietary standard, or any other kind of solution, the vendors must get on board or be left behind. The more progressive vendors try to get in on the ground floor of new developments in these areas so that they are ahead of their competitors. It is not, and never has been, an issue of technology. The technology problems can be solved. The political and social / business problems bind us, and leave us stumbling around in the dark. Some vendors may actually wish to undermine developments that could render their products of lesser value. Their business and their livelihood are sometimes threatened. Progress in the field of technology development, and of standards and systems working together is a never ending struggle between two opposing forces: those who would have open, non-proprietary solutions to interoperability and similar issues, and those who would have their products and systems purchased and used by most of the industry, perhaps becoming de facto standards.

Until we find a way for compromise in this struggle, or a way for users to combine in force to insist that vendors work together in pre-competitive developments for the benefit of all industry, we will be facing these issues for all time to come. However, these issues can and have been successfully resolved in other technical disciplines, as illustrated by the PC and printer example given earlier. If there is a will with collaboration, cooperation, coordination, and harmonization (the 3Cs+H), the metrology interoperability issues can also be solved.

4. Appendices

4.1. List of Registrants

The following were registered for the *International Metrology Interoperability Summit* (IMIS) hosted by the National Institute of Standards and Technology (NIST) on March 28-30, 2006 in Gaithersburg, Maryland and most registrants also attended IMIS.

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4.2. List of Acronyms

The following acronyms are either used in this document or supporting documents such as plenary presentations contained in the appendix. Each acronym is expanded to its text equivalent and, where appropriate, a brief definition or explanation is also provided.

API – Application programming interface – An application programming interface (API) is the interface that a computer system, library or application provides in order to allow requests for service to be made of it by other computer programs, and/or to allow data to be exchanged between them.[iii]

AIAG – Automotive Industry Action Group: Headquartered in Southfield, MI, the AIAG is a globally recognized organization founded in 1982 by managers from DaimlerChrysler, Ford Motor Company, and General Motors, to provide an open forum where members cooperate in developing and promoting solutions that enhance the prosperity of the automotive industry.[iv]

CAD – Computer Aided Design

CAM – Computer Aided Manufacturing

CAE Computer Aided Engineering

CMM – Coordinate measuring machine

CMSC – The CMSC is an international organization of users, service providers, and manufacturers of high precision measurement systems, reverse engineering systems, software, and peripherals. These systems include laser trackers, photogrammetry, scanning devices, CMM's, and global positioning systems. The society promotes the advancement in use or development of any measurement system or software that produces and uses three-dimensional coordinate data. (www.cmsc.org)[v]

COM – Common object model

CORBA – Common Object Request Broker Architecture – the interface definition language (IDL) used by DMIS Part 2

DMIS – Dimensional Measuring Interface Standard – "DMIS is the definitive standard for communications of dimensional measurement program sequences and results for manufacturing inspection. DMIS is widely used with coordinate measurement machines (CMMs), either as an intermediate file format between a CAD system and the CMM's native proprietary inspection language, or as a native programming language for direct control of the CMM."[vi]

DMIS, Part 1 – DMIS began as a textual syntax and has grown into a full inspection programming language from its origins as a neutral interchange format between CAD systems, CMMs, and results reporting systems. This syntactic portion of the DMIS standard is referred to as "DMIS, Part 1".

DMIS, Part 2 – DMIS, Part 2 is a companion standard to DMIS Part 1, and defines an object oriented programming interface for on-line communication between a DMIS execution system and external applications. This interface permits the definition of features, tolerances, sensors, coordinate systems and other DMIS entities; the loading, execution, and interactive editing of part programs; the

querying of machine and program status; and notification of activity by the inspection device to interested external applications. It further defines programming interfaces for modularizing the equipment control and add-on mathematics. In essence, DMIS Part 2 defines an application programming interface (API) for defining, controlling, accessing, and watching items of interest within a CMM, using direct calls within a high level programming language (such as C++ or Java).[vi]

DML – In its most widely used form, DML stands for *Data Manipulation Language*. However, in the context of dimensional metrology, the acronym stands for *Dimensional Markup Language*. DML is an XML format definition tailored to the needs of dimensional results for discrete manufacturing. The purpose is to haul the results between applications that generate or use dimensional information. A typical scenario is where an inspection device collects dimensional data and sends the information to an SPC package for process analysis or a database for long-term storage.[vii]

DMSC – Dimensional Metrology Standards Consortium, Inc.

DNSC, DSC – DMIS National Standards Committee, DMIS Standards Committee – DSC is the official consensus body for the Dimensional Measuring Interface Standard (DMIS). The purpose of the Committee is to continually develop, maintain, and support the DMIS standard, and also to work with other groups to identify and develop related industrial automation standards. The DSC works closely with national and international standards bodies to harmonize efforts, and to produce relevant documents or standards that will promote the interoperability of systems.[viii]

EDUG – European DMIS Users' Group – a not-for-profit organization of companies that use DMIS or provide DMIS solutions.

ERM – Enterprise Resource Management describes software that manages all of a company's assets and resources, including such basic applications as general ledger, accounts payable and receivable, as well as manufacturing, inventory, and human resources.[ix]

GD&T – Geometric Dimensioning and Tolerancing

I++DME – Inspection-plus-plus/Dimensional Measurement Equipment – is an initiative sponsored by Audi, BMW, DaimlerChrysler, Volkswagen and Volvo with the objective of increasing efficiency, reducing manufacturing times and costs by reaching the interoperability of software and hardware components used in automated dimensional inspection. I++/DME is a specification that defines application protocols for a dimensional measurement equipment interface. The syntactic structure of I++ is patterned after c++. The purpose of the specification is to allow a dimensional inspection part program to run on different brands of coordinate measuring machines, provided that the specification is supported by the specific CMM.[x]

IDL – Interface Definition Language

MEPT – The Metrology Project Team is organized under the Collaborative Engineering and Process Development Steering Committee of the Automotive Industry Action Group (AIAG). (The Metrology Project Team is also sometimes referred to as **MIPT**, for Metrology Interoperability Project Team.) The goal of the Metrology Project Team is to reduce product development cycle time and manufacturing costs by achieving interoperability of the software and hardware components used in automated metrology. This team's main goal is to provide a single voice of the user in specifying interoperability requirements. This organization is an "umbrella" group that oversees all the metrology interface standards efforts worldwide, without competing with existing standards organizations such as the Dimensional Metrology Standards Consortium (DMSC).[xi]

NIST – National Institute of Standards and Technology

OEM – Original Equipment Manufacturer

ORB – Object request broker

PLM – Product Lifecycle Management

STEP – The Standard for Product Model Data Exchange (also known as ISO 10303) is a data standard created by an international team of more than 500 CAD, CAM and CAE experts. STEP gives an explicit and complete representation of product data throughout its entire life cycle. STEP first became an ISO standard in 1994 and over the last five years all of the leading CAD software vendors have implemented STEP data translation. It is estimated that more than two million CAD stations now contain STEP data translators.

STEP AP – "AP" stands for *application protocol*. The STEP standard is divided into many Application Protocols belonging to the ISO 10303 family of standards. Each protocol defines a data exchange standard for a defined family of products at a defined stage in its life cycle. The most popular Application Protocols for CAD are AP-203 also known as ISO 10303-203, and AP-214 also known as ISO 10303-214. Other application protocols pertinent to metrology interoperability are those for process planning (AP-240) and dimensional measurement (AP-219).

STEP NC – STEP-NC is an extension of STEP that defines a machine independent bidirectional data standard for Computerized Numerical Control (CNC) systems. Using STEP-NC, an external system such as a CAM or CAD/CAM system can create machine independent CNC instructions for making a part. Any CNC machine tool that has the necessary resources should be able to process the STEP-NC data. It is intended to replace G codes with a richer data set, including features, geometry and tolerances. (All of the above step-related references come from the STEP NC website.)[xii]

XML – eXtensible Markup Language – a flexible way to create common information formats and share both the format and the data on the World Wide Web, intranets, and elsewhere.[xiii]

4.3. Reference list of Applicable Standards by their best known reference numbers, with a title and a short description

ASME B89 – A series of technical specifications for dimensional metrology and the calibration of instruments.

ASME Y14.41-2003 – *Digital Product Definition Data Practices*, sets forth the requirements for geometric dimensional data, tolerances, and other annotations in CAD models.

ASME Y14.5-1994 – The standard for geometric dimensioning and tolerancing (GD&T) in two-dimensional drawings.

DMIS 5.0 Parts 1 and 2 – (ANSI and ISO Equivalent) Dimensional Measuring Interface Standard

ISO 10303 – Equivalent to STEP (see STEP)

STEP – **ST**andard for the **E**xchange of **P**roduct model data (equivalent to ISO 10303), comprises a series of Application Protocols (APs) that address specific components of the data exchange process.

STEP AP 203 – Configuration controlled design – defines the geometry, topology, and configuration management data of solid models for mechanical parts and assemblies.

STEP AP 213 – Numerical control process plans for machined parts.

STEP AP 214 – Core Data for Automotive Mechanical Design Processes (applicable and used in other domains).

STEP AP 219 – Dimensional Inspection Information Exchange..

STEP AP 223 – Application Protocol for the exchange of design and manufacturing product information for cast parts.

STEP AP 224 –Mechanical product definition for process plans using machining features.

STEP AP 238 – CNC controller plug-ins

STEP AP 239 – Product life-cycle support

STEP AP 240 – Process plans for machined parts.

4.4. Detailed Description of the Workshop Methodology used at the International Metrology Interoperability Summit (IMIS)

The first day of the workshop was devoted to understanding the *metrology interoperability landscape*. The workshop provided a structured forum in which recognized metrology experts made presentations to the entire group in plenary sessions. The morning session comprised presentations from interoperability-enabling organizations and presentations that described interoperability-enabling technologies. The afternoon session comprised presentations on interoperability perspectives from specific stakeholders, and included both end users and vendors (equipment and software manufacturers). The contents of many of the presentations are available for download as described in the Appendix in section 4.6.

During the second day of the workshop, participants divided into four groups that worked in parallel to address interoperability issues involving *product definition*, *inspection process definition*, *process execution*, and *analysis and reporting of quality data*. Each group was assigned a facilitator and a scribe, and the group was strongly encouraged to follow templates that were designed to gather information and gain consensus in support of the development of the roadmap. By working in small groups, participants were able to make contributions in their areas of expertise that added to the cumulative body of knowledge.

Each group began by creating an *activity diagram* that graphically illustrated the business and operational workflow for the group's topic area. Some groups were able to produce both a "current state" and a "future vision" activity diagram. The activity diagrams identified the *key functions* required to perform the activity, and were used in the *current-state assessment* of the technology area. The groups were asked to address the following during their assessment:

- Identify *key functions* in the activity where a lack of interoperability causes "pain" (deficiencies) – Tabulate the problem areas and attempt to quantify the magnitude of the problem in terms of cost, capability, or uncertainty.

- Identify barriers to achieving interoperability – What barriers exist that keep us from eliminating the pain? Why does the issue prevail and why has it not been resolved?
- Identify emerging best practices that eliminate the "pain" and overcome the barriers – What best practices exist or are emerging that point to the solution?

After completing the activity diagram for the current-state, each group was asked to define a *vision* for the desired future state for each key function. The elements of the vision should include the *issues* – identified areas of "pain" and barriers to success, as well as the directions in which the emerging best practices are pointing. An *issue* is defined in this context as any technology void, cultural attribute, or process characteristic that impedes progress or is a barrier to the optimal successful execution of the subject key function. Issues and key functions do not necessarily align with one another. Groups were asked to identify and tabulate issues regardless of whether they were generic and crosscutting or applicable to specific products, processes, etc.

Emphasis was placed on the fact that the workshop is a building process – each step using the work before and building on that work to create information for the roadmap. From the *current state* and *vision* discussion, a few key issues that support an interoperable solution will emerge. While there is no magic number, four to ten issues for a topic area should be reasonable. It is important to keep the issues at a fairly high level because there will be other levels added to the hierarchy. To put the issues in a context that many of us can relate to, issues are "program level" ideas. They may be:

- *Product-Specific* – Issues that deal with design or performance of the activity. Ask the question; are there issues associated with a product or class of product? Are there specific issues associated with any sector or application?
- *Process-Specific* – Issues that deal with execution of the topic. Are there processes or activities that lead to the identification of issues? For example, inspecting large structures with laser trackers might raise different issues than a touch probe for a CMM.
- *Other* – Standards, emerging technologies, disruptive technologies, infrastructure. Are there issues that fall into the catch-all categories? What emerging technologies could greatly change the metrology landscape to the point that they would be considered disruptive technologies? What practices (e.g. process certification) present issues? What emerging technologies or practices would be implemented if cultures were changed or infrastructure was not an issue?

During the workshop, the *current state* and *vision* presented by each group was captured in tabular and textual format in a Microsoft® Word® document. In addition to identifying issues, each group compiled *solutions*, *actions*, and *supporting information* that were used to develop the roadmap.

Solutions – To resolve an issue, one or more solutions must be delivered and supporting goals must be achieved. Think in terms of critical capabilities such as technology tools, standards in place, business processes unified or integrated, etc. This is the "project" level. There should be several solutions for every issue, and don't forget that it is important to include parallel solutions with decision points.

Actions – For every solution, there are actions that must be performed. This is the lowest detail level of the roadmap. This is the task level, and the information captured should be adequate to provide a descriptive title from which a task plan could be developed.

Supporting information – It is important that the roadmap provide the quantification necessary to assess the importance and value of the solution. Therefore, additional information will be solicited.

The above information was captured in a Word® document during the workshop that will be subsequently used to populate a time-phased roadmap template, using the structure shown in Table 8.

In an ideal world, the *Supporting Information* would be generated at the *Actions* level (tasks) and rolled up to the *Solutions* level (projects). However, the time available during the workshop was short, and there was much to do. For that reason, each group was asked to flesh out the *Supporting Information* at the *Solutions* level first and fill in information at the *Actions* level as time allowed. The following definitions apply to the elements of the roadmap shown in Table 8.

Table 8. This sample Roadmap graphic is designed to present the issues by technology area. The information conveyed includes the priority of the issues, the metrics to be used in maturation, and actions needed to achieve success.

Priority	WBS	Roadmap Hierarchy	Metric	FY2007	FY2008	FY2009	FY2010	FY2011
	1	Topic Area (e.g. Product Definition)						
	1.1	Issue:						
F M H	1.1.1	Solution:	Definition of Metric	Maturity Start	Action Benefit Cost	Maturity Final		
	1.1.2	Solution			Maturity Start	Action Benefit Cost	Maturity Final	
	1.1.3	Solution				Maturity Start	Action Benefit Cost	Maturity Final

Timeline – placing the activity on the timeline and showing the time from start to completion show the duration of an activity. To simplify the task, the letters *S*, *M*, and *L* were used with the understanding that *S* is zero to three years, *M* is three to seven years, and *L* is seven to ten years

Priority – For each solution, define a priority of H (High), M (Medium), or F (Future). "F" is used to denote solutions that are valuable but not near enough in time to merit a high priority for near-term action. "F" is in deference to the fact that no activity that has a low priority should make it onto the roadmap.

Metrics – For each solution, define the measure of success. Metrics such as "50% reduction in costs" or "20% reduction in the number of parts inspected" are applicable.

Organizational issues– identify any organizational barriers that must be overcome or changes that must be made.

Manufacturing Readiness Level [MRL] (start and finish) – Technology Readiness Levels and Manufacturing Readiness Levels are becoming a common element of the language of technology investment. For broad acceptance of our roadmap, it is important that TRLs be assigned. Definition of Technology Readiness levels are given in Appendix 4.5.

Benefit – Quantify the impact or delivering this solution. Without detailed analysis, place a business value on the result of delivering the solution.

Cost – For each activity, assign a rough order of magnitude estimate of the cost of delivering a solution. Do not think in terms of fully burdened costs with all interested parties receiving funds, but think of a, well-managed effort that delivers cost-effective results.

Following this introductory section, this document presents a technology plan that is based on input from each of the four groups. The plan comprises information on the current state, vision for the future state, important issues with their solutions, and a technical roadmap for each technology area. Important crosscutting issues that do not clearly fall within the scope of one of the four areas of focus are also identified and addressed.

4.5. Technology Readiness Levels.

Table 9. Technology Readiness Levels in the Department of Defense (DOD).

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Example might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and 'flight qualified' through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system 'flight proven' through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

4.6. Plenary Presentations

Images of approximately 700 slides from the plenary presentations and dinner presentations are available in a separate appendix to supplement this document. The decision was made to separate the slides from this document so that it would be small enough to send to workshop participants by e-mail. You may download the plenary presentations appendix after May 4, 2006, at http://imti21.org/metrology/.

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