SANDIA REPORT

SAND2018-14160
Unlimited Release
Printed December 2018

Model Authorized Product Realization (MAP-R) Analysis

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@osti.gov
Online ordering: http://www.osti.gov/scitech

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.gov
Online order: http://www.ntis.gov/search

SAND2018-14160
December 2018
Unlimited Release

Model Authorized Product Realization (MAP-R) Analysis

Adrian Miura
Product Life Cycle Management
Sandia National Laboratories
Albuquerque, New Mexico 87185

Eric M. Moyer
Human Factors
Sandia National Laboratories
Albuquerque, New Mexico 87185

Siobhan Heiden
Human Factors
Sandia National Laboratories
Albuquerque, New Mexico 87185

Curtis W. Brown
Model-Based Enterprise
Kansas City National Security Campus
Kansas City, Missouri 64147

Alan Markel
Quality Engineering
Kansas City National Security Campus
Kansas City, Missouri 64147

Eric Walling
Purchase Process Engineering
Kansas City National Security Campus
Kansas City, Missouri 64147

Abstract

The Model Authorized Product Realization (MAP-R) project was a collaboration between Sandia National Laboratories (SNL) and Kansas City National Security Campus (KCNSC) to advance the Nuclear Security Enterprise's (NSE) ability to quantify the differences between the current drawing centric/drawing-based process and a part centric/model-based process. In short, MAP-R identified the key business benefits of the part centric model-based process using quantifiable data. MAP-R builds upon the past, but leverages current advances in technology, processes/standards, and the motivation of our current workforce to use a part-centric/model-based design and manufacturing method.

This page intentionally left blank.

TABLE OF CONTENTS

Table of Contents

FIGURES

TABLES

NOMENCLATURE

Abbreviation	Definition
3DIV	3D Interactive Viewable
ACO	Advanced Change Order
BoC	Bill of Characteristics
CER	Complete Engineering Release
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
DA	Design Agency
DTER	Drawing Transfer Engineering Release
EA	Engineering Authorization
FBTol	Feature-Based Tolerancing Advisor
FCO	Final Change Order
GD&T	Geometric Dimensioning and Tolerancing
HFE	Human Factors Engineering
IMPRINT	Improved Performance Research Integration Tool
IT	Information Technology
LEP	Life Extension Program
LOTAR	Long-Term Archival and Retrieval
MAP-R	Model Authorized Product Realization
MBD	Model-Based Definition
MBE	Model-Based Enterprise
MBIT	Model-Based Integrated Tools
ML	Material List
NASA	National Aeronautics and Space Administration
PA	Production Agency
PDM	Product Data Management
PMI	Product and Manufacturing Information
PO	Purchase Order
POQR	Purchase Order and Quality Requirements
PPD	Purchase Product Definition
QAIP	Quality Assurance Inspection Procedure
QE	Quality Engineer

Abbreviation	Definition
SA	Situation Awareness
SART	Situation Awareness Rating Technique
SXR	Specification Exemption Release
TDP	Technical Data Package
TLX	Task Load Index
WR	War Reserve

This page intentionally left blank.

1. INTRODUCTION

Aerospace and defense companies are rapidly moving to a Model-Based Enterprise (MBE) on the promise that it will provide a competitive advantage. The axiom "better, faster, cheaper" is liberally applied as the business motivation in adopting this new paradigm. This statement often is followed up by anecdotal data, a PowerPoint presentation, and some handwaving. Early in 2016, The National Institute of Standards and Technology (NIST) released the results of their study to quantitatively assess the merits of using Model-Based Definition in a report titled Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection. This was the first published comprehensive study that quantified the differences between a drawing-centric and model-centric product definition method for manufacturing and inspection. The design and results of this study became the catalyst for a joint project between Sandia National Laboratories (SNL) and the Kansas City National Security Campus (KCNSC).

The Model Authorized Product Realization (MAP-R) project was a collaboration between SNL and KCNSC to advance the Nuclear Security Enterprise's (NSE) ability to quantify the differences between the current drawing-centric/drawing-based process and a part-centric/model-based process. In short, MAP-R identified the key business benefits of the part-centric model-based process using quantifiable data. MAP-R built upon the past but leveraged current advances in technology, processes/standards, and the motivation of our current workforce to use a part-centric/model-based design and manufacturing method.

Designed to follow a structured process flow from design, through manufacturing and inspection, the MAP-R project executed each process for a control (drawing-based) and an experimental (model-based) track. All of the tracks were analyzed in-course and post hoc to compare a multitude of data items and to identify key differences and areas of improvement. To determine the differences regarding human performance of the two methods (the control and the experimental), Human Factors Engineering (HFE) analysis methodologies were applied to the study of each process and human interaction with the reference materials. Data collected focused on task analysis, situation awareness, cognitive workload, and time-to-completion. Various methodologies were employed such as ethnographic observation, where HFE analysts observed the design and manufacturing engineers perform their prescribed tasks in situ, and collected task data on activities and recorded behaviors of note. Cognitive walk-throughs were used to generate task data on activities that could not be observed in-person, through detailed interviews of the task performers. Workload analysis and modeling methods were employed, based on more well know workload load data collection and modeling techniques including the application of the National Aeronautics and Space Administration (NASA) Task Load Index (TLX) (Hart and Straveland, 1988) and Multiple Resource theory (Wickens and Yeh, 1986). Finally, situation awareness of the participants was assessed by applying the Situation Awareness Rating Technique (SART) (Taylor, 1989). These techniques and tools were employed to gather data that was then analyzed to characterize human performance differences between the two processes.

The project utilized existing IT infrastructure and tools for both the drawing and Model-based Definition (MBD). However, to execute the MDB, new processes for defining and authoring a part-defining model and additional training for the designer on how to use the MBD features of the CAD tool were necessary. The team developed and released issue A of 9925020 titled (U) IDENTIFICATION, PART DEFINING MODEL, 3D CAD, as the method to authorize a part-defining model.

Although the results from the human factors workload analysis did not show a significant overall time savings (approximately 6 hours) as depicted in Figure 1-1, it did reveal that model-based tools can detect design issues that could increase manufacturing costs and decrease product reliability errors early on in the process that were not detected with the drawing-based tools. Additionally, as depicted below, it also illustrated that by using the part-centric model-based methods there was a noticeable decrease in the time spent by the engineers and technicians in the "high" workload condition (approximately 11 hours). This is in part due to a decrease in high workload activities for the model-based process, such as human or manual transcription of data, as well as other reasons as discussed later in the report. Activities high in mental workload, such as manual data transcription, can have a high probability of error based on the amount and complexity of the tasks.

Total Execution Time	
Drawing-based	Model-based
89:23:14	83:50:11

Time in Low Workload	
Drawing-based	Model-based
19:56:31	18:22:28

Time in Med Workload	
Drawing-based	Model-based
5:24:38	12:08:38

Time in High Workload	
Drawing-based	Model-based
64:02:05	53:19:05

Figure 1-1 Overall MAP-R Workload Analysis Results.

Note that additional timing data was collected, and those results do show a more notable difference between the drawing-based and model-based processes. This data is discussed in more detail in each use case, as well as in Section 6, Conclusions.

2. PREVIOUS WORK

The MAP-R project used the National Institute of Standards and Technology (NIST) study Testing the Digital Thread in Support of Model-Based Manufacturing and Inspection as the starting framework. Additionally, the team reviewed the following previous pilot projects and reports:

- Model-Based Engineering, A strategy for RRW and future weapons program
- Model-Based Product Realization (MBPR) SAND2003-3228P
- Model-Based System Engineering SAND2015-5834M
- Model-Based Product Acceptance https://prod.sandia.gov/techlib/auth-required.cgi/2004/043849c.pdf

This page intentionally left blank.

3. THE CURRENT STUDY

MAP-R was structured to follow a logical progression from design to manufacturing to inspection that culminated in the production of physical parts, and the simulated execution of the National Nuclear Security Administration's (NNSA) Quality Assurance Inspection Procedure (QAIP). There were initially 8 major activities (high-level use cases) that were decomposed in to a minimum of 16 detailed activities. However, as the project progressed, it became clear that further granularity was needed in the manufacturing use cases. In the end there was a total of 14 major activities (high-level use cases) that were decomposed into a minimum of 28 detailed activities. That is, each activity had both a control activity (current method) and a model-based activity. This structure enabled the direct comparison and data collection of activities between the current and model-based processes. Figure 4-1 describes the scope of MAP-R. SNL performed activities that culminated in the authorization of product definition. KCNSC used the authorized product definition to start their manufacturing activities. KCNSC produced the parts using traditional subtractive manufacturing methods. Finally, the parts were accepted by NNSA using a simulated Quality Assurance Inspection Procedure (QAIP).

3.1. Purpose

MAP-R was the NSE's first case study comparison between a drawing-based and a model-based design and manufacturing process. The SNL and KCNSC MAP-R project's primary purpose was to understand the MBE value proposition for the enterprise. This report describes the drawing-based and model-based processes, resulting content, and HFE data collection activities, analyses performed, and the results for the MAP-R project. From this data, the report defined how MBE can be used to further understand the benefits and challenges of implementing MBE for product realization.

3.2. Hypotheses

The primary hypothesis for the human factors analysis of this study was derived from the need to determine which of the two analyzed processes promote greater performance in terms of a lower probability of errors and greater efficiency in terms of time savings, over the entire end-to-end design and manufacturing process. By varying the reference materials (2D versus 3D), the team assumed that the individuals completing the activities associated with these processes used those materials in differing ways. The team attempted to measure these differences through a number of analyses, with the goal of discovering their magnitude. With this in mind, the primary hypothesis sought to determine *if there was a difference between the two processes concerning how much time was spent on each of the use cases analyzed, in a high workload condition*. The details of how the team determined this, and the reasons for measuring workload, are discussed in greater detail in Section 3.4.2.

3.3. Constraints and Assumptions

Initially, and through the course of this project, there were a number of important points of consideration that needed to be taken into account to compare the two processes. These are:

- The drawing-based process is the current process used by the SNL and KC manufacturing and design engineers and technicians. It has been executed multiple times over many years, and these are established experts. In contrast, the model-based process includes many tasks that are relatively new to the performing engineers and technicians. This must be recognized since there was most likely a learning curve for the performance of many of the activities while using the 3D reference material.
- The 3D reference material has not undergone formal usability evaluations, and while it possesses much potential, the way in which information is presented by the material will greatly affect its utility, for better or worse.
- Due to the nature of activities performed, the data collection was not the same for all use cases. The activities for some use cases were observed directly by an engineer, while some were analyzed post hoc through cognitive walkthroughs, and finally some were only discussed. However, when it came to the quantitative analysis, the data was collected and analyzed to the same level as best as possible. Those use cases where the data collection could not meet the same standards were reported on anecdotally and indicated as such in the report as required.

3.4. Analyses Performed

The MAP-R project included two analysis efforts to help characterize the difference between the employment of the two reference materials. A design engineering timing analysis was performed in concert with detailed human factors analyses. For some use cases, both analyses were performed when possible, but for some, human factors data was not able to be captured due to the scope and timing of activities. These activities are discussed in more detail Sections 3.4.1 and 3.4.2.

3.4.1. Timing Analysis

Throughout the MAP-R project, participants for each use case maintained a spreadsheet indicating start and end time for each sub-activity in the use case. The times collected measured time-on-task and not duration.

3.4.2. Human Factors Evaluations and Data Collection

The goal of the Human Factors Engineering (HFE) effort for the Model Authorized Product Realization (MAP-R) project was to determine the differences, in regard to human performance and interaction with the reference materials, of the two defined design and manufacturing processes. Data collected focused on task elements, situation awareness, cognitive workload, and time-to-completion. Various methodologies such as ethnographic observation, task analysis, cognitive walk-through, workload analysis, and situational awareness assessment were employed to gather these data that were then analyzed to characterize human performance differences between the two processes.

3.4.2.1. Human Factors Evaluations

A number of HFE data collection, analysis, and evaluation techniques were employed for this effort, including:

- Task Analysis
- Cognitive Walkthrough
- Ethnographic Observation
- Workload Analysis
- Workload Questionnaires
- Workload Model
- Workload Levels
- Situational Awareness Assessment

Each technique and its application to this project is described below.

3.4.2.1.1. Task Analysis

A task analysis is a comprehensive process that seeks to understand all activities that occur on the part of a discrete individual or team employing a defined set of tools or methods, surrounding the accomplishment of a specific goal (Kirwan & Ainsworth, 1992). Task analyses are performed to ensure that engineers and analysts completely understand the scope of activities, techniques, tools, and methods for an identified task or set of tasks. Once completed, the task analysis can be used as the basis for additional analyses to define the performance of the humans involved (Hackos & Redish, 1998; Kirwan & Ainsworth, 1992). Task analyses consist of a functional analysis, task inventory, and task flows; each are described below with respect to this project.

Functional Analysis – Functional analysis aims to determine the functional steps of the scenarios used to achieve a goal with a system, device, or process under specific conditions (Hackos & Redish, 1998; Alexander & Maiden, 2004). For MAP-R, we adopted 14 use cases, detailed in Section 4, for analysis of process functions.

Task Inventory and Task Flow – Generating task inventories and task flows is a foundational approach that provides the basis of analysis for human performance and workload evaluations. After the process functions for each use case were defined, the use cases were then analyzed and broken down into individual tasks, from which task inventories and flows were assembled. This was accomplished by either interviewing or observing individual engineers or technicians while they performed operations, and recording step-by-step activities of their processes. This approach allowed for an in-depth understanding of the actual tasks and subtasks performed by the operator and provided insight into task sequences and task dependencies, as well as user motivations. As much as possible, time-to-completion data were also collected for each subtask as well as the overall tasks for each process. These data provided general information on task duration and variability.

3.4.2.1.2. Cognitive Walkthrough

A cognitive walkthrough is a detailed evaluation procedure that aims to simulate and map an operator's problem-solving process at each step of a task (Lewis et al., 1990; Nielsen, 1995). This method was performed in conjunction with or after the task analysis was created, and involved in-depth analysis of the activities performed by the operator to determine which tasks are high in cognitive workload. Like task analysis, the cognitive walkthrough allows for understanding of tasks and subtasks. However, this method is concerned more with the cognitive elements of the tasks performed, which are often unobservable. These cognitive elements or processes may include recalling information from memory, deciphering between information components, or mitigating process environmental or task elements. For this project, the main output of the cognitive walkthrough was the identification of procedural tasks that were high in cognitive demand. These tasks were then further examined by ethnographic observation and workload analysis, each of which are described in following sections.

3.4.2.1.3. Ethnographic Observation

Ethnography is the process of collecting data about users or tasks in their normal environment (Fetterman, 1998). Ethnographic observations are field-based and holistic, in which the analyst observes users and tasks to gain a full understanding of the group being studied. Analysts may probe for additional information using interviews (formal and informal) of users, particularly community experts (Spradley, 1979). Findings from ethnographic observations, in combination with data from other collection methods, can inform the design of products, processes, and systems (Blomberg, Burrell, & Guest, 2003). For this study, ethnographic observations, which included interviews, were used in tandem with other data collection methods. The findings gave insights into various process and user characteristics (e.g., environmental factors and user attitudes) and provided context for noteworthy or unexpected findings and results.

3.4.2.1.4. Workload Analysis

Workload refers to "the amount of work and number of things to do; time and the particular aspect of time one is concerned with; and/or the subjective psychological experience of the human operator" (Cain, 2007). The image in Figure 3-1, from Yerkes and Dodson (1908), depicts the relationship between performance and engagement/stress (labeled arousal, in 1908 terms), which has come to be accepted as the basic model for understanding human performance in relation to stress. Additionally, we can then assume that as a task or set of tasks requires more effort, cognitively or otherwise, the associated workload to complete those tasks rises, and as it crosses some threshold of tolerance of the individual their performance starts to wane, and their stress level rises. This is essentially the current theory of analyzing workload as a predictor of individual performance for a task or set of tasks (Yerkes, Dodson, 1908; Swain, 1964; Paas, 1992). While the concept of high workload or workload overload is often discussed, we cannot forget the concept of low workload, or workload underload. Workload underload is when the individual is essentially bored with a task and therefore is not engaged in it, which would also result in a detriment to performance.

Measuring workload allows for better understanding of the performance demands of given tasks, which improves prediction of operator and system performance (Cain, 2007). For this project, the mental workload of the operators was analyzed using data collected from observations to construct workload models and validated questionnaires. The questionnaires and models are each described in more detail by use case in Section 4.

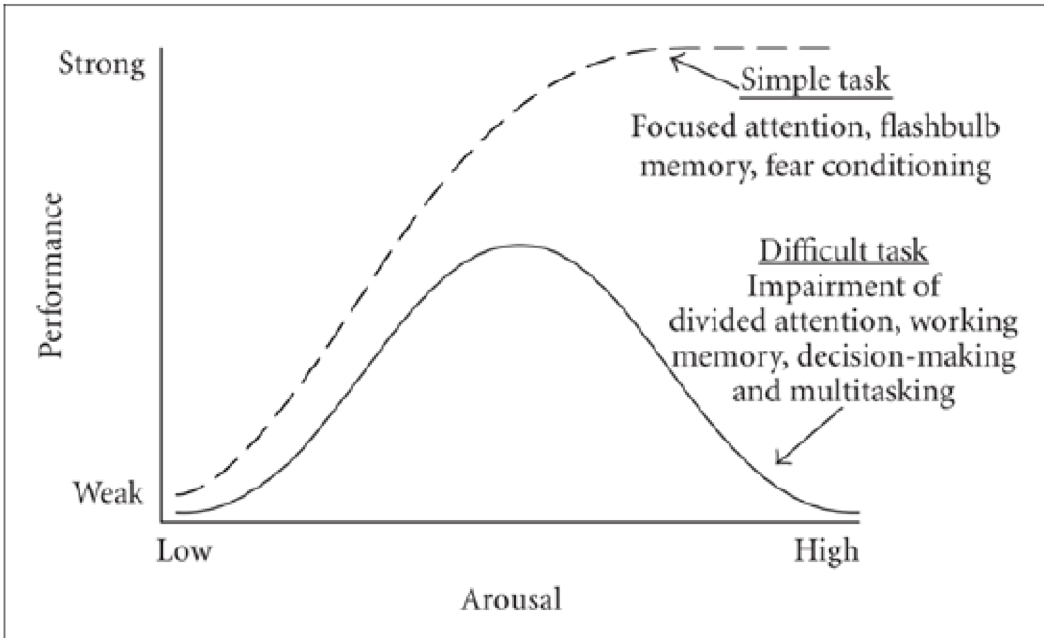


Figure 3-1 Yerkes and Dodson (1908) Arousal/Engagement/Stress Curve.

3.4.2.1.5. Workload Questionnaires

The workload questionnaires administered were the National Aeronautics and Space Administration (NASA) Task Load Index (TLX) and the TLX Task Demand Comparison Questionnaires (Hart & Staveland, 1988). These questionnaires aim to understand the level of workload with respect to specific tasks or sub-tasks associated with a larger goal or operation. The TLX questionnaire solicits subjective workload levels for mental demand, physical demand, temporal demand, performance, effort exerted, and frustration from participants upon task completion. The Task Demand Comparison questionnaire is used to determine weightings for the six subjective workload categories based on participant feedback. Using the TLX data and the weighting from the Task Demand Comparison Questionnaire, a composite score for overall subjective workload is calculated. A score of 74 or greater indicates above average workload according to research performed by Hart and Staveland (1988). Subsequently, a score below 74 is considered an acceptable workload level. See Appendix A for the NASA TLX and Task Demand Comparison Questionnaires.

For this project, the questionnaires were administered for applicable use cases following interviews or observation activity where possible. Weighted workload scores were then calculated to identify any potential perceived workload overload conditions and as anecdotal indicators of task activities that might require further analysis.

3.4.2.1.6. *Workload Model*

Workload models for both the drawing-based and model-based processes were constructed and analyzed in the Improved Performance Research Integration Tool (IMPRINT) (Mitchell 2000, 2003; Salvi 2001) for selected critical use cases in order to get a detailed understanding of the effects the reference materials may have had on the performers (see Section 4 for more detail). IMPRINT is a discrete event, simulation, and modeling software tool that allows the user to input quantifiable system parameters and task flows. The simulated task flows are run over a certain amount of time to produce an estimated measure of workload. For each task in the task network, the software computes the time-to-complete the task flow, along with overall workload. Note that workload parameters in IMPRINT differ than those used in the workload questionnaires. In IMPRINT, workload is based on the VACP (visual, auditory, cognitive, and psychomotor) (McCracken & Aldrich, 1984) theory and the Multiple Resource Theory (MRT) of workload (Wickens & Yeh, 1986). These theories postulate that each individual possesses channels of capacity from which resources can be utilized to complete differing types of tasks. Tasks draw resources from different channels, and this in essence is a measure of the difficulty of the task in question, with more difficult tasks drawing more resources from more channels. These methods allow an analyst to build tasks in a task flow, assign them workload resource channel values, execute task flows temporally, and then observe the level of workload an individual is under at any given time, based on the tasks they are performing. These tasks generate a model of their workload for specific activities. The core of the model revolves around the resource cost values assigned to each task. These values are selected based on pre-existing research and task type, as well as the findings from the task analyses, cognitive walkthroughs, and ethnographic observations.

The IMPRINT models are the primary means of the computation and comparison of the workload of the two differing processes used for this study. These results are presented and discussed in Section 4.

3.4.2.1.7. *Workload Levels*

In order to provide a means for resolving the team's hypothesis, detailed in Section 3.2, a metric was derived by which the workload models of the use cases between each process could be compared to one another in terms of time spent by the task performer, in the pre-determined workload levels of low, medium, and high. These levels were determined by the total workload values obtained from the workload models over time, and delineated as low (0-14.9), medium (15-18.9), and high (19-21). These values were determined based on the MRT scores for task types, where 21 is the maximum of possible workloads to be experienced for the three channels modeled, and the concept of stress-based workload levels and predicted performance. These values are detailed for each use case and process in Section 4.

3.4.2.1.8. Situational Awareness Assessment

At a high level, Situational Awareness (SA) can be understood simply as "what is going on" (Endsley, 1995). SA as proposed by Endsley (1995) consists of three levels: perception, comprehension, and projection. Perception (level 1) consists of perceiving the status, attributes, and dynamics of relevant elements of the environment. Comprehension (level 2) involves the synthesis of elements in level 1 to understand how it will impact the individual's goals and objectives. Projection (level 3) involves the extrapolation of those elements' potential impact on future states of the operational environment.

To assess operators' SA of specific elements of the MAP-R processes, an industry-validated questionnaire was used. The Situation Awareness Rating Technique (SART) (Taylor, 1989) was administered following either the ethnographic observations or the cognitive walkthrough interviews depending on the time and availability of the operators. SART was used in addition to other workload measures because it is generally accepted that more demanding activities (i.e., high workload) will negatively impact the operator's SA of non-critical activities in a specific process. As such, SART is an indirect measure of cognitive workload. The results were analyzed for anecdotal indications of high workload through low SA ratings. See Appendix A for the SART questionnaire.

3.4.2.2. HFE Findings and Adjudication

All HFE findings collected were provided to Design Engineering along with recommended process modifications to address concerns. These results will be provided in a way that facilitates Design Engineering's implementation of recommendations based on impact to process, lifecycle timeline, and the resources available.

3.5. Drawing-Based Current Process

The traditional drawing-based approach is where the product definition is authorized as a part-defining drawing. In this process, the 2D static drawing is a PDF and is the legal and functional definition.

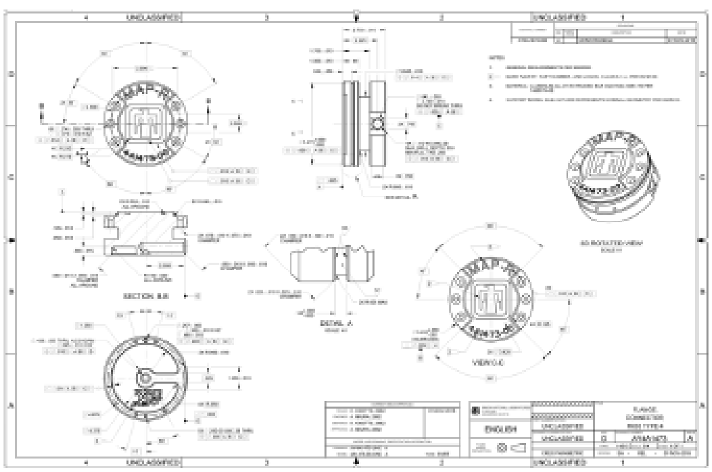


Figure 3-2 Drawing-based Paradigm.

3.6. Model-Based MAP-R Process

The new model-based enterprise paradigm approach is where the product definition is authorized as a part-defining drawing. In this process, the 3D model-based definition is the legal and functional definition.

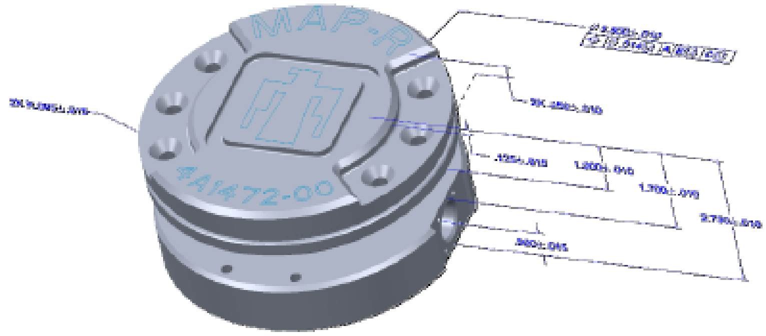


Figure 3-3 Model-Based Paradigm.

4. MAP-R ACTIVITIES ANALYZED

Use cases were identified that encapsulated the design and manufacturing process and acted as the basis for comparing the drawing-based and model-based processes. These use cases are listed below and displayed in Figure 4-1.

- Use Case 1: Create Product Definition
- Use Case 2: Certify Product Definition
- Use Case 3: Create LOTAR Equivalent Files
- Use Case 4: Authorize Product Definition
- Use Case 5: Disposition Product Change
- Use Case 6: Prepare for Manufacturing
- Use Case 7: Create Derivative Files for Manufacturing
- Use Case 8: Package Product Definition for Manufacturing
- Use Case 9: Manufacture Part
- Use Case 10: Prepare for Inspection
- Use Case 11: Inspect Part
- Use Case 12: Request Product Change
- Use Case 13: Create Quality Assurance Inspection Procedure (QAIP)
- Use Case 14: Perform Engineering Analysis

These use cases are described in more detail in the following sections. Each use case section is organized as follows:

- Description of the tasks involved in the use case
- Human factors data including workload model information and post-activity survey results
- Activities and errors identified in the use case based on findings from task analysis, cognitive walkthroughs, and ethnographic observations
- Findings of note and recommendations for mitigating challenges and potential errors inherent in the use case

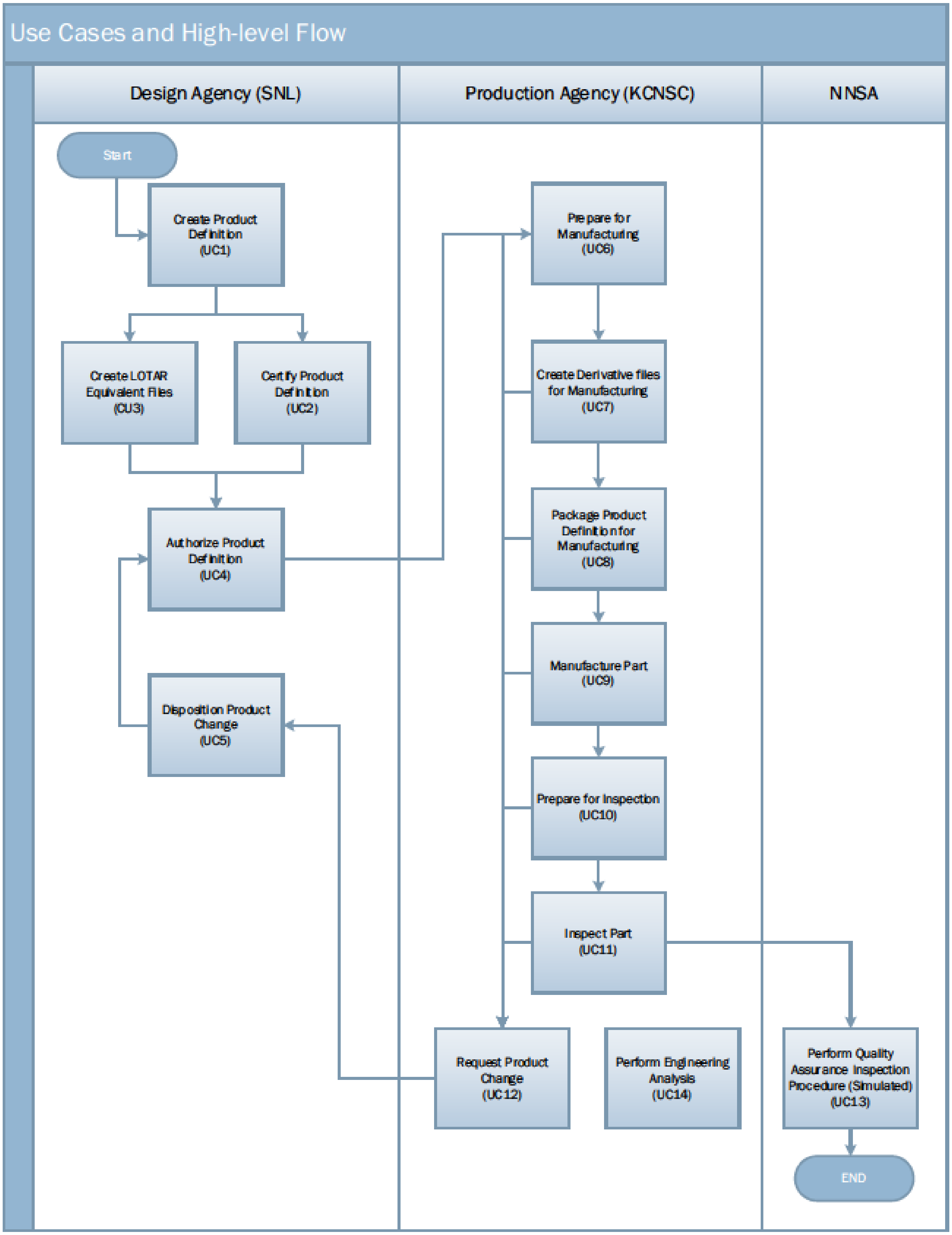


Figure 4-1 MAP-R Design and Manufacturing Use Cases.

4.1. Use Case 1: Create Product Definition

4.1.1. Description

This use case includes creating the drawing or model that contains the Product and Manufacturing Information (PMI), and generating the Materials List (ML).

4.1.2. Drawing-Based and Model-Based Differences

For the Create Product Definition use case, note the differences between the drawing-based and model-based processes.

The drawing-based process requires creating a 2-dimensional (2D) print as a PDF that must include all relevant information, views, and PMI from the 3-dimensional (3D) model. This 2D print is used for producing downstream models, inspection, and qualification and serves as the primary reference for the manufacturing contractor.

The model-based process does not require this task. However, an additional task is needed to generate views or combination states that logically aggregate the PMI of the 3D model. These combination states are almost as difficult to create as the model itself since the design engineer needs to ensure all relevant Geometric Dimensioning and Tolerancing (GD&T) is annotated on a selection of views.

4.1.3. Human Factors Data

4.1.3.1. Workload Models Comparison

Figure 4-2 and Figure 4-3 detail the IMPRINT workload graphs for the drawing-based and model-based processes. Note that while the first portions of these models are identical, the model-based process took longer to complete than the drawing-based process (19:49:42 versus 12:24:30). This was due to the added step of creating the combination states, which adds effort to the model-based version of this use case. This situation is discussed in more detail in Section 4.1.5.

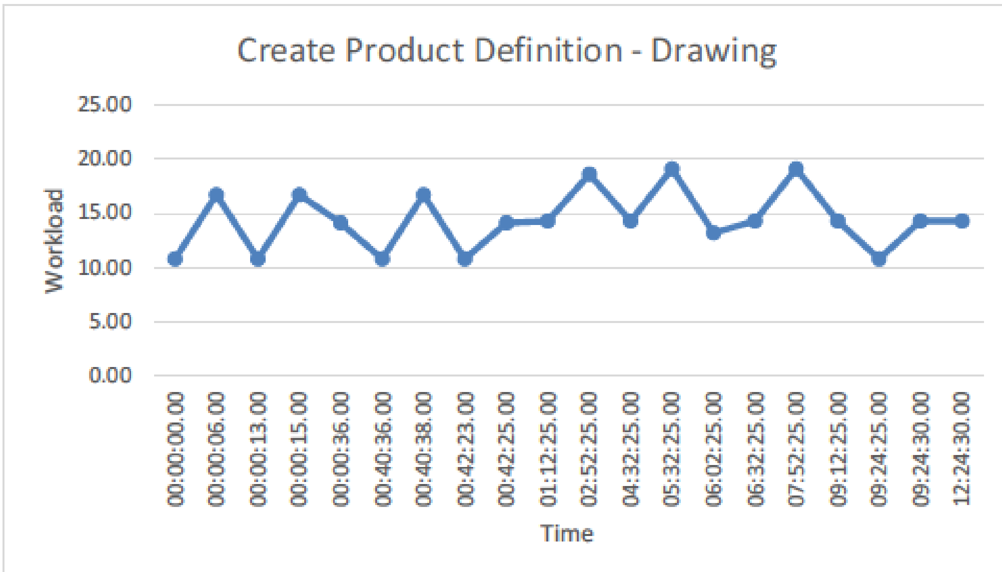


Figure 4-2 Create Product Definition – Drawing-Based Workload Model.

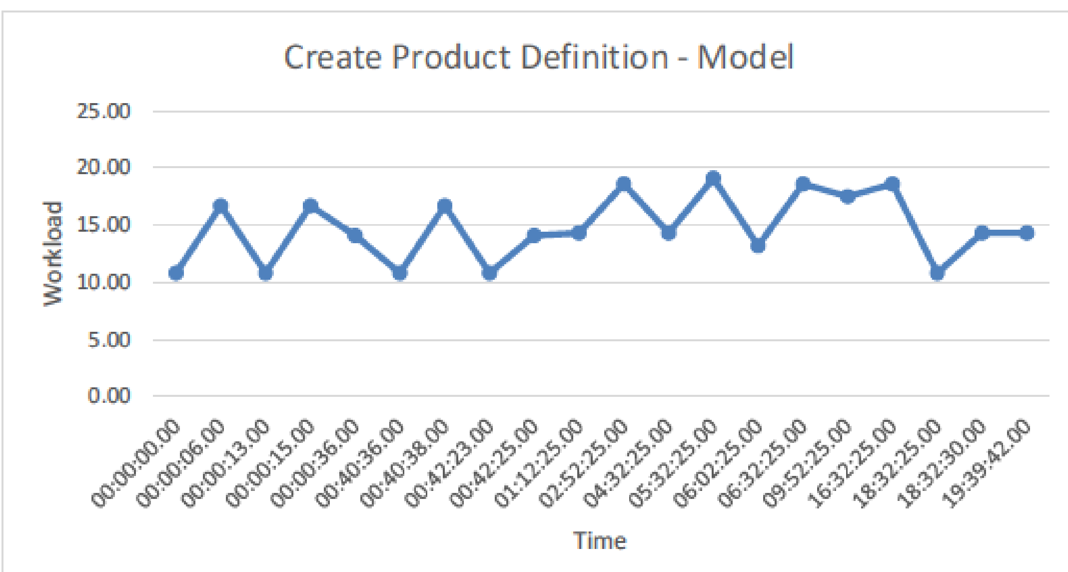


Figure 4-3 Create Product Definition – Model-Based Workload Model.

More detail is available on the differences in workload between the two processes when comparing task time spent in workload level conditions. Figure 4-4 displays total task time in low, medium, and high workload level conditions. These conditions are defined as the sum total time of tasks being executed, where the workload values were less than 14 (low), between 15 and 18 (medium), and 19 and up (high). The maximum possible value for workload at any given time in the model is 21. Note that the workload values employed in the model are discussed in more detail in Section 3.4.2.1.

Time at Workload Level for Create Product Definition - Drawing

Low	Med	High
0-14	15-18	19 - 21
8:52:17	0:02:13	3:30:00

Time at Workload Level for Create Product Definition - Model

Low	Med	High
0-14	15-18	19 - 21
5:27:29	6:42:13	7:30:00

Figure 4-4 Time at Workload Levels for Create Product Definition.

From the data in Figure 4-4, the product definition use case workload model for the model-based process exhibits more time spent in the high workload condition than the drawing-based model. Refer to Section 4.1.5 for more information about this comparison and possible reasons for these differences.

Figure 4-5 depicts the workload model for creating the materials list, and Figure 4-6 displays the time in workload levels. Note that this task is the same for both processes, since regardless of method employed, the user must create a materials list to support the materials chosen for the component.

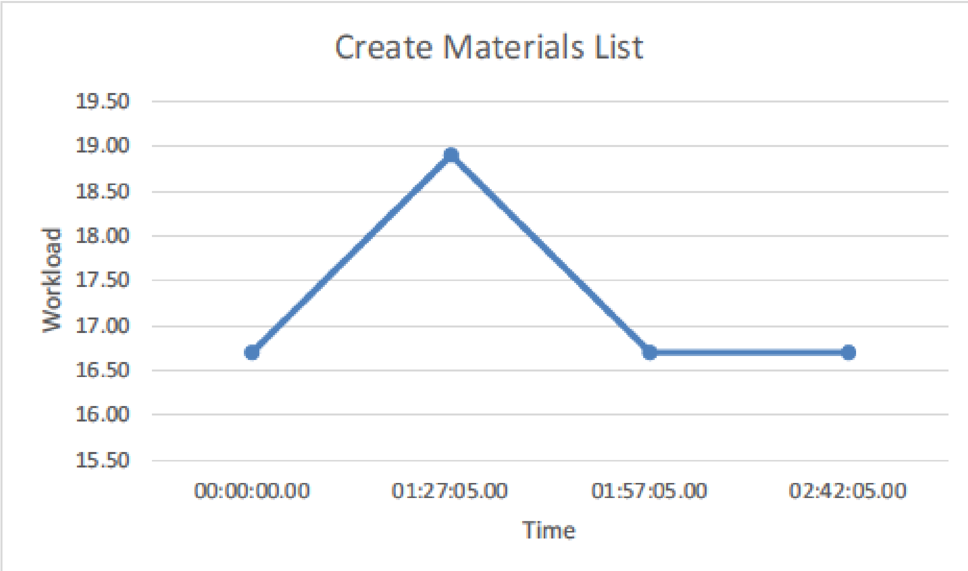


Figure 4-5 Create Materials List Workload Model.

Time at Workload Level for Create Materials List

Low	Med	High
0-14	15-18	19 - 21
0:00:00	2:12:05	0:30:00

Figure 4-6 Time at Workload Levels for Create Materials List.

4.1.3.2. Survey Data

The results of the NASA TLX showed evidence that the design engineer experienced high levels of workload for the "Create combination states" task, with high levels of Mental Demand (85) and Frustration (90).

Results from the SART agreed with the TLX in that the design engineers indicated an overall low level of SA (4) while performing the "Create combination states" task, with indications that the situation was highly unstable (7), complicated (7), and contained a high number of variables (7). The Review ML task and subtasks also seemed to score low overall (9). These findings indicate it might be worth investigating these subtasks in more detail to identify possible mitigations.

4.1.4. Activities and Errors

The tasks analysis effort uncovered information about possible error rates of the observed activities. Both the drawing-based and model-based processes include a large number of activities that could elicit errors over time for creation of a single part. Any activity involving copying text from one location to another, either physically (writing by hand) or digitally (typing by looking), will be associated with a chance for error (~1%, Grudin 1983). This may not be important to the project as a whole, depending on which product the error was committed. It can often result in unwanted delays, minor or otherwise, completing the process or project.

Some instances occurred within the drawing-based and model-based processes that required the engineer to type information from one source product to another, rather than being "copy and pasted." These were:

- *Creating the materials list (ML)* – During this process, engineers must transcribe materials and properties that include a large number of numerical fields that need to be typed and transcribed by hand into the required fields for the Materials List (ML). There is an elevated chance of error during this process.
- *Transcribing ML to the Creo® part file* – After the ML is created and approved, the information from it is added to the Creo part metadata file. This process is a manual digital process and includes an elevated chance of error.

These two activities are good examples of the most error-related activities with the processes. While there are other instances where errors can arise, all materials were reviewed multiple times prior to release, although these reviews were also subject to possible errors. The best solution to avoid these types of errors is to automate the process so information shared across products can be easily copied and pasted from one product to another, or populated automatically, once the data is selected by an engineer. How these processes can be automated requires further evaluation and is not part of this study.

4.1.5. Findings of Note

During the ethnographic observations and interviews for the drawing-based and model-based processes of this use case, there were a number of findings generated that lend insight into the challenges of both processes. The list below provides these findings and discusses possible mitigations.

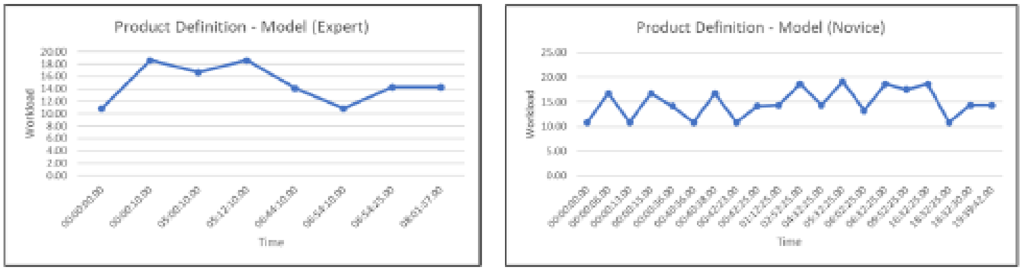
Findings for both processes:

- The "Determine material specification" step is performed early in this use case for both the drawing-based and model-based processes. It is done using lengthy searches in the IMS on the Sandia Classified Network (SCN). Once located, the materials spec(s) must be down-shifted or hand-carried, and then the unclassified information from it hand-copied into the appropriate products in the PMI. This process is lengthy and cumbersome, and the manual transfer of information from a hard copy to electronic elevates the likelihood of errors. If modified to allow for automation in some fashion, the likelihood of error would decrease.

- As discussed above, there are two steps in the early phases of this use case for either process that require manual data entry from one product to another. These steps are "Creating the materials list" and "Transcribing the ML to the CREO part file" and would benefit with some analysis on how to automate them to reduce the likelihood of errors.

Findings for the model-based process:

- As seen with the workload models for this use case, Figure 4-2 and Figure 4-3, the model-based process took longer to complete than the drawing-based process. This was reported by the engineer to be primarily due to the task for generating the combinations states, which was "very cognitively time-consuming." Ultimately, the engineer needed to guess which view or views provided the best information and feature groupings to convey the design of the part adequately. Each combination state includes a view of the part, coupled with notations, chosen to communicate a feature in the most clear and concise way. Each of these views then went under increased scrutiny from the review team and had to be changed multiple times. This part of the process is still being refined, and it is possible that once there is an established process and engineers gain more expertise, the time to completion will be reduced. Providing a way to simplify the creation of the combination states should also be considered, since currently these are created and modified by manipulating the part model in Creo. This should be analyzed for standardization and efficiency in future iterations of the process.
- This was the first iteration of the model-based process for this use case, and it is expected that a learning curve will be seen in the task performance times as the engineers involved become more familiar with the process and perform faster as skill level and confidence increase. The time difference between novice and expert task performers is well documented in human performance literature, and it is common for experts to perform up to 40% faster than novices for procedure-based skills (Judkins et al., 2008; Wiedenbeck, 1985; Lazonder et al., 2000). Therefore, most likely this time will decrease for the model-based process based solely on skill acquisition over time. In response to this observation, a second iteration of this use case for the model-based reference material was completed and a workload model was generated from the data collected. Although the resulting data was not used in the overall workload and timing analysis, Figure 4-7 depicts the data from this activity and compares it to the first iteration demonstrating the difference between the novice and expert in the creation of the part defining model (full PMI).



Time at Load		
Low 0-14	Med 15-18	High 19-21
1:17:37	0:12:00	6:32:00

Total Time 8:01:37

Time at Load		
Low 0-14	Med 15-18	High 19-21
5:27:29	6:42:13	7:30:00

Total Time 19:39:42

Figure 4-7 Expert vs Novice Workload and Time for Product Definition.

This page intentionally left blank.

4.2. Use Case 2: Certify Product Definition

4.2.1. Description

This use case includes the activities associated with inspecting the Creo model manually, running CADIQ® to analyze the model, using Feature-Based Tolerance to analyze the Parasolid® model, then finally creating the 3-Div that will be used for the manufacturing. This part of the process is used to ensure that the model contains all necessary information and that the geometry is correct to ensure the manufacturability of the part.

For the traditional drawing-based approach, the primary check of the product definition involves reviewing the 2D drawing (i.e., PDF) for shape and GD&T. Since the 2D drawing is generated from a source model (i.e., Creo native model), for a Creo model it may or may not be checked for agreed design and business practices using a PTC® tool called ModelCheck™. For the MAP-R project instance, the Product Realization Team (PRT) conducted the certify product definition activity with five full time equivalents (FTE) reviewing the 2D drawing 13 hours each (65 hours). Upon conclusion of this review, the PRT deemed it approved for engineering release for fabrication.

For the new model-based enterprise paradigm, the model would become the part-defining model; therefore, the model was checked. For the MAP-R project, this involved running ModelCheck to confirm that NSE design and business practices were being followed. More importantly, the source model (i.e., Creo native model) was geometry-checked by running the CADIQ tool. Next the model's PMI was analyzed by KCNSC's Feature-Based Tolerancing Advisor (FBTol) tool and the PMI. This part of the process is used to ensure that the model contains all necessary information and that the geometry is correct to ensure the manufacturability of the part.

4.2.2. Drawing-Based and Model-Based Differences

There was a difference between the two activities. The engineers using the traditional 2D drawing reference material spent much time reviewing the 2D drawing for both the shape, GD&T, and notes. For the new model-based enterprise paradigm, model-based tools such as the CADIQ model checker and FBTol were utilized prior to the (human) review for manufacturability and GD&T notational compliance to standards.

The CADIQ geometry checker became a key benefit for the MBE process. Once the MBD was completed, CADIQ was run against the model and within a few minutes, two critical geometry issues were identified that were missed by the 65+ hour 2D drawing review. One issue was that a .009" thin wall (thickness of aluminum foil) was identified. This was significant enough that the design shape was modified to mitigate the issue.

4.2.3. *Human Factors Data*

4.2.3.1. Workload Models Comparison

Figure 4-8 and Figure 4-9 display the workload graph and time at workload levels for the Certify Product Definition use case. This data is presented for posterity and was included in both processes, as presented here, and in the overall workload analyses discussed in Section 3.4.

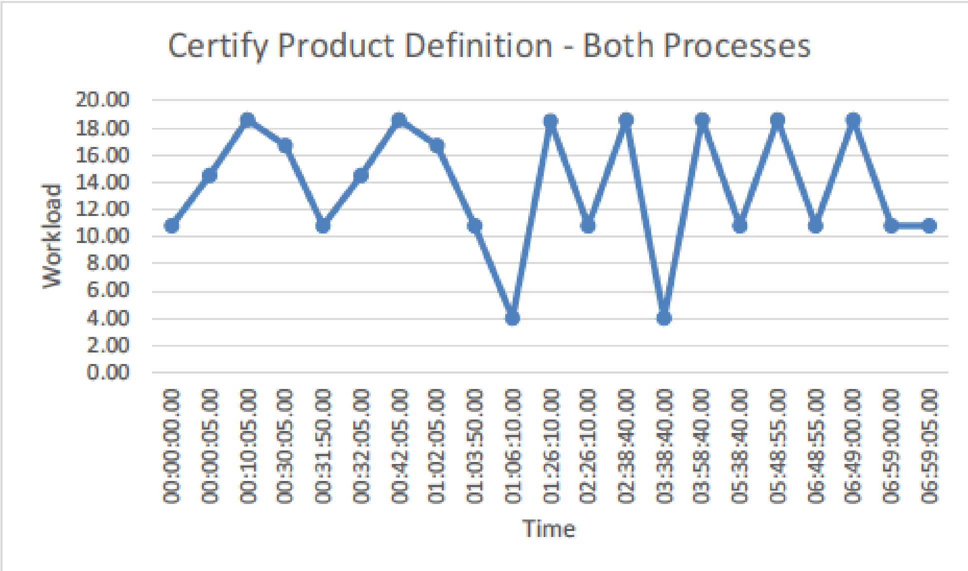


Figure 4-8 Certify Product Definition – Workload Model.

Time at Workload Level for Certify Product Definition – Drawing and Model

Low	Med	High
0-14	15-18	19 - 21
1:25:35	0:03:30	5:30:00

Figure 4-9 Time at Workload Levels for Certify Product Definition.

4.2.3.2. Survey Data

Survey data was not collected on this process; however, the interviewed engineer did not report any concerns over the effort required to perform the tasks associated with this use case.

4.2.4. Activities and Errors

While a good portion of the work involved in this use case is automated, human-in-the-loop analysis of the automatically generated data is required. These tasks consist of reviewing issues flagged by the software to determine if they are indeed truly issues or false positives. For most simple parts, the software will find anywhere from 2 to 5 issues, but it could be as high as 20 or 30 issues for more complex parts. However, all of these need to be reviewed by an engineer to filter out the false positives, which are usually most of the issues. All issues found and verified must be fixed, and this process is accomplished by generating a Product Change, found in Use Case 5: Disposition Product Change.

4.2.5. Findings of Note

The new model-based paradigm allows early detection of issues before engineering release. There was an issue discovered in the MAP-R part through the completion analyses involved with this use case. Essentially, one of the features had a wall that was extremely thin. Fortunately, the model-based paradigm allowed the PRT to find this before engineering release, and the solution was identified and implemented relatively quickly.

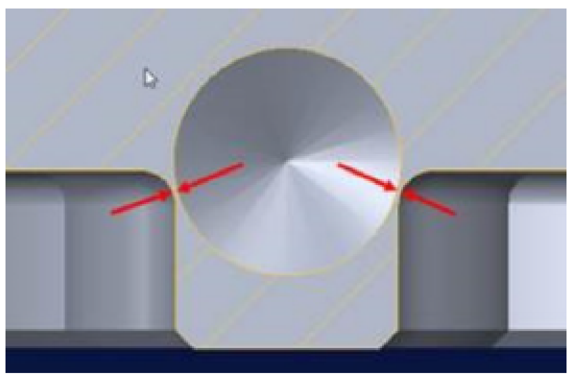


Figure 4-10 CADIQ Analysis of Thin Wall Issue.

This page intentionally left blank.

4.3. Use Case 3: Create LOTAR Equivalent Files

4.3.1. Description

This use case involves preparing and then merging all materials and files for long-term archival and retrieval (LOTAR). For the traditional drawing-based approach, LOTAR was accomplished through a 2D static drawing in PDF format and STEP AP203 for the support model (geometry only). For the new model-based enterprise paradigm, using recently approved STEP AP242 was identified as the LOTAR of record. This section discusses the tasks performed and the workload model created; however, no differences between the two tasks were observed.

4.3.2. Drawing-Based and Model-Based Differences

There are no differences for this use case between the two processes.

4.3.3. Human Factors Data

4.3.3.1. Workload Models Comparison

Figure 4-11 and Figure 4-12 display the workload graph and time at workload levels for the LOTAR use case. This data was presented for posterity and was included in both processes, as presented here, in the overall workload analyses discussed in Section 3.4.

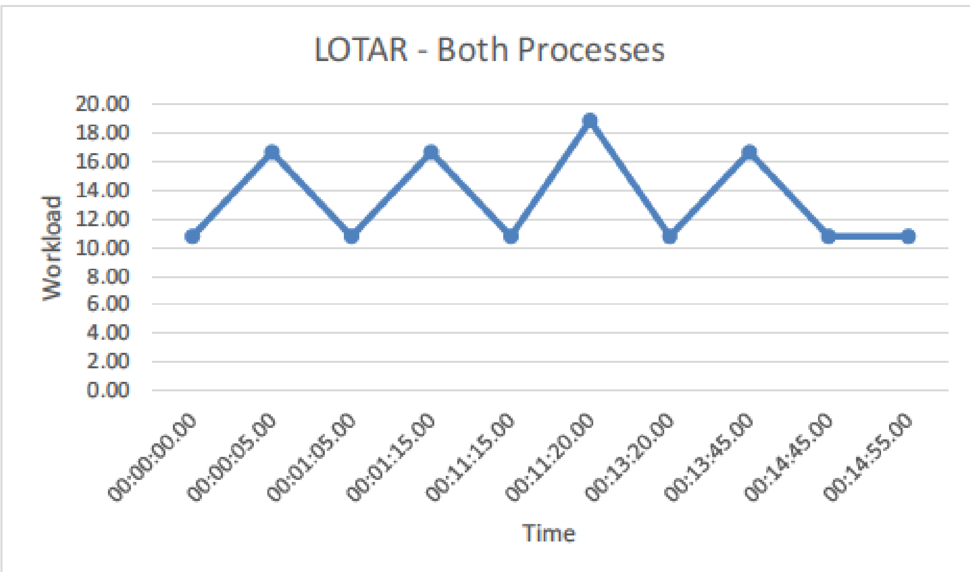


Figure 4-11 Create LOTAR Equivalent Files – Workload Model.

Time at Workload Level for Create LOTAR Equivalent Files – Drawing and Model		
Low	Med	High
0-14	15-18	19 - 21
0:00:55	0:12:00	0:02:00

Figure 4-12 Time at Workload Levels for Create LOTAR Equivalent Files.

Analysis of this data does demonstrate relatively high levels of workload for brief periods of time, but the amount of time spent in the high workload condition is minimal (2 minutes), and the overall task execution time of 14 minutes and 55 seconds minimizes the concern of mental fatigue induced errors.

4.3.3.2. Survey Data

None of the scores on the NASA TLX, for the tasks of this use case, were 75 or over (high workload); however, the first task ("Save file as AP242") was comparatively higher than the others (score of 68). This may point to the need to analyze whether the required task steps decrease difficulty, but could also be due to skill level. Conversely, there were some low scores on the SART for the first 3 tasks, "Save file as AP242" = 2; "Edit header file" = -2; "Review files and header" = 8. This generally means that the individual performing the tasks is fully engaged, with little to no ability to direct attention elsewhere. As discussed in section 3.4.2 this could lead to more mental fatigue induced errors over time. See section 4.3.5 for more information.

4.3.4. Activities and Errors

For this use case, there were a number of activities that the interviewed designer indicated were challenging and subsequently could be improved for the sake of preventing errors when these tasks are being performed repeatedly.

- For the first task, "Save file as AP242," this was the first time it was executed with Creo 4. So, there was a learning curve, but also some parameter selections required to ensure the file saves correctly. These selections were not able to be saved in the software, and thus would have to be done every time a file is saved.
- There is a manual text entry activity required when the designer needs to edit the header file for the second task of the use case. As with previous use cases, there are a number of places where the designer needs to hand-type copied information from another source. This type of activity carries with it an elevated rate of error.

4.3.5. *Findings of Note*

As mentioned above, it would benefit this use case if two things could be changed to reduce the likelihood of errors.

- Determine how to save the selectable parameters for generating the AP242 file. This would streamline this use case and minimize errors associated with incorrectly saving the file.
- Analyze the manual data copying task and determine if it is able to be automated. Automation could greatly reduce or eliminate the likelihood of transcription errors.

This page intentionally left blank.

4.4. Use Case 4: Authorize Product Definition

4.4.1. Description

This use case involves two primary tasks. The first task involves creating the Complete Engineering Release (CER). The second task, and the bulk of this use case, includes the activities of analyzing all materials referenced in the CER, for their authorized use to product the part and release to long-term archival and retrieval (LOTAR). Data was collected and compared for both of these tasks for both processes.

4.4.2. Drawing-Based and Model-Based Differences

The primary differences between the drawing-based and model-based processes for this use case involve creating a baseline for the model-based process, completing the tasks associated with peer reviewing, and maintaining control of the drawing set for the drawing-based process. The peer review process includes time-intensive activities and numerous manual review tasks that are not needed with the model-based process.

4.4.3. Human Factors Data

4.4.3.1. Workload Models Comparison

Figure 4-13 and Figure 4-14 depict the workload models for the "Create CER" task for this use case. A comparison of these models shows that they are relatively similar, with the model-based task taking slightly longer to include creation of the baseline. Again, as with many other tasks in this overall process, there are instances where the engineer needs to manually copy information from one item to another. These instances are where their workload was the highest. Furthermore, Figure 4-15 displays the time in workload levels for the create CER task.

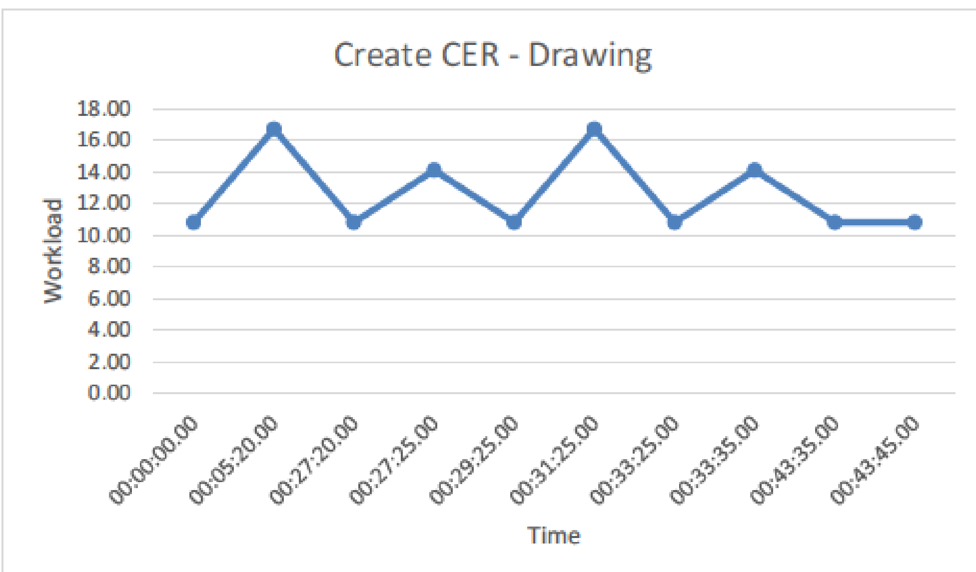


Figure 4-13 Create CER – Drawing-Based Workload Model.

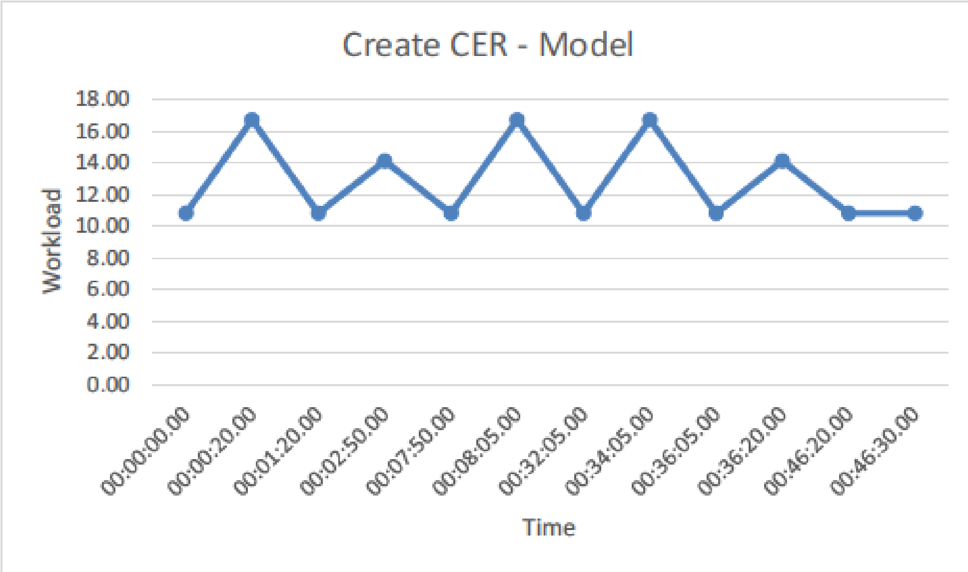


Figure 4-14 Create CER – Model-Based Workload Model.

Time at Workload Level for Create CER - Drawing

Low	Med	High
0-14	15-18	19 - 21
0:19:45	0:24:00	0:00:00

Time at Workload Level for Create CER – Model

Low	Med	High
0-14	15-18	19 - 21
0:19:30	0:27:00	0:00:00

Figure 4-15 Time at Workload Levels for Create CER.

Figure 4-16 and Figure 4-17 detail the workload models for both processes. The overall level of workload was similar for both the drawing-based and model-based processes. However, the drawing-based process did take longer than the model-based process, and apparent within the graph for the model-based process are three large workload spikes. These spikes are associated with the manual inspection tasks of the materials drawing-based process review materials. It may be possible to mitigate these with automation, but would require further analysis.

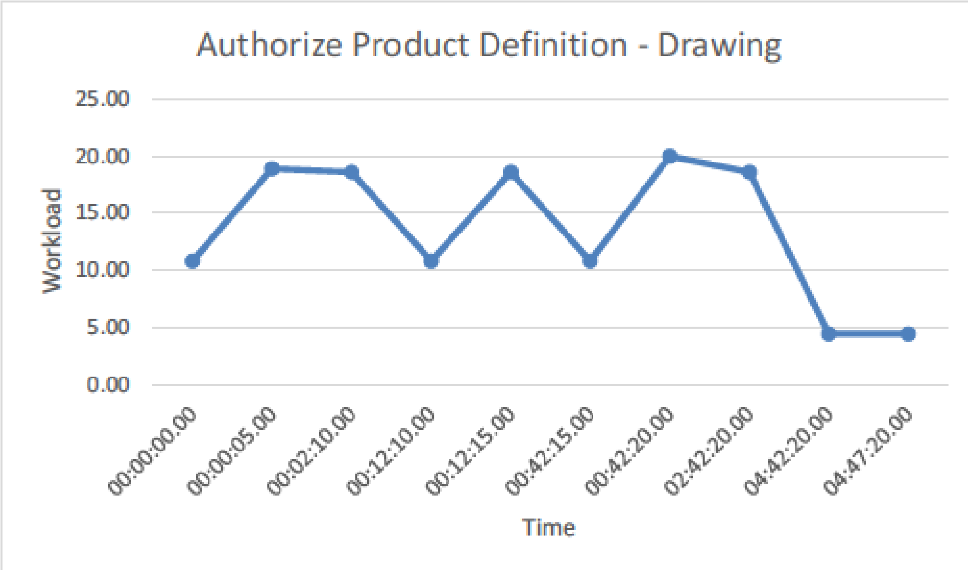


Figure 4-16 Authorize Product Definition – Drawing-Based Workload Model.

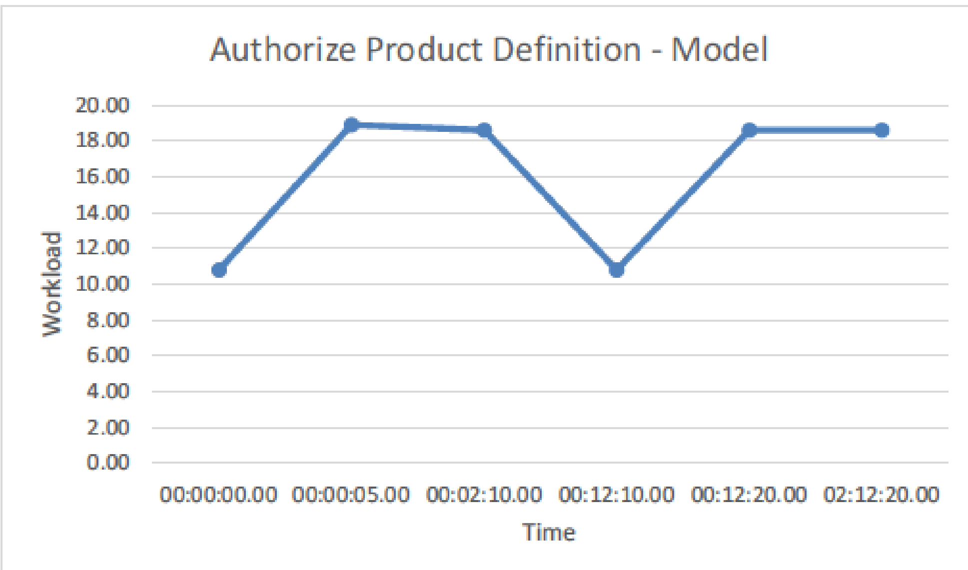


Figure 4-17 Authorize Product Definition – Model-Based Workload Model.

Figure 4-18 further documents the differences between the two processes regarding time at workload level.

Time at Workload Level for Authorize Product Definition - Drawing

Low	Med	High
0-14	15-18	19 - 21
0:05:15	0:00:00	4:42:05

Time at Workload Level for Authorize Product Definition – Model

Low	Med	High
0-14	15-18	19 - 21
0:00:15	0:00:00	2:12:05

Figure 4-18 Time at Workload Levels for Authorize Product Definition.

Figure 4-18 shows that the drawing-based process requires more time in the high workload condition due to more cognitively demanding tasks being executed over longer periods of time. More detail on the activities and differences for these tasks can be found in sections 4.4.4 and 4.4.5.

4.4.3.2. Survey Data

The results of the NASA TLX survey indicated that none of the tasks performed, for either of the processes, were high workload. Results from the SART survey agreed with the TLX in that the overall level of SA was fairly high while performing all use case tasks for both processes.

4.4.4. Activities and Errors

This use case, for both processes, includes activities that could elicit a high number of errors when performed repeatedly over time. Any activity involving comparing and cross-referencing data manually will introduce an increase in the possible errors that can be committed (1-2%, Melchers & Harrington, 1982). For the drawing-based process, there were instances that required the document control specialist to review and cross-check information from one source product to another. These were:

- Examine the Drawing Transfer Engineering Release (DTER). During this process the document control specialist review the EA to ensure SNL has maintenance of the product definition and ensure all drawings listed on the Complete Engineering Release (CER) are released in to IMS and that the numbers and titles are correct. There is an elevated chance of error here during this process, and in fact, an error was made mistyping a value in a text file during this process. This lends more credence to the need for automation of text copying across files in the process.
- Inspect drawings/models. During this activity the document control specialist must examine each drawing and/or digital model to ensure they are complete. It is a lengthy manual inspection process and includes an elevated chance of error.

These tasks are not needed for the model-based process and therefore reduce the overall workload. For the drawing-based process, it is not immediately apparent how this use case could be modified to reduce or eliminate the high workload inspection activities from being performed manually. It is possible that they could become automated in the future, but how this is done precisely needs to be part of a follow-on evaluation.

4.4.5. Findings of Note

During the ethnographic interviews for this use case, there were a number of findings generated that lend insight into its challenges. The list below provides these findings and discusses possible mitigations.

- The interviewed product definition specialist reported that there were a large number of backlogged CERs and that it is a never-ending stream of work for the inspecting specialists. This lends credence to the need for automation within this process, but how to implement such automation needs to be determined carefully through follow-up studies.
- The large amount of manual comparison tasks in the drawing-based process for this use case could lead to increased chances of error. While there are fewer of these types of activities for the model-based process, automating these types of tasks would help even further. However, how this task can be automated should be analyzed separately.

This page intentionally left blank.

4.5. Use Case 5: Disposition Product Change

4.5.1. Description

This use case involves the activities associated with documenting and dispositioning changes, both before and after an engineering release initiated by a product change request.

4.5.2. Drawing-Based and Model-Based Differences

For the model-based product definition, both shape and PMI were checked before engineering release. CADIQ was used to check the model and FBTol was used to check the PMI. Both tools detected issues that were corrected before engineer release. This saved time and money as issues were identified early and were more affordable to correct. Further on, both the drawing-based and model-based required some engineering changes. The traditional drawing-based experienced an Advanced Change Order (ACO) then Final Change Order (FCO), whereas the model-based MAP-R paradigm experienced two FCOs. For KCNSC, the documented time toward reviewing disposition of the product change is as shown in Table 4-1.

Table 4-1 Disposition Product Change Timing Data.

Traditional Drawing-Based	Model-Based (MAP-R) Paradigm
n/a	6.58 hours

4.5.3. Human Factors Data

Human factors data was unable to be collected for this use case.

4.5.4. Activities and Errors

No errors were recorded or observed for this use case.

4.5.5. Findings of Note

No significant process findings of note were uncovered during this use case.

This page intentionally left blank.

4.6. Use Case 6: Prepare for Manufacturing

4.6.1. Description

This use case involves the process planning activities associated with a purchase process engineer at KCNSC fabricating the part. The Prepare for Manufacturing use case started with a KCNSC process meeting involving the process, purchase, and quality engineer. Since the MAP-R parts were to be treated as a War Reserve (WR) product, the process needed to establish demand within the KCNSC business system to produce a part. Once the demand was in place, the product definition (e.g., drawing or MBD) was reviewed and a determination was made to purchase the product. Next, the purchase engineer created an Item Setup and prepared a Purchase Product Definition (PPD). The PPD contains all part-defining drawings and specifications necessary to produce and inspect the product at the vendor. Finally, the PPD was released to the Buyer for obtaining a vendor to fabricate the part. Once a fabrication vendor was selected, the vendor was debriefed with first submittal of definitions.

4.6.2. Drawing-based and Model-based Differences

The two primary differences for this use case involve which product definition was reviewed and what content of the PPD was provided to the Buyer and ultimately the vendor. For the traditional drawing-based process, the ML and AY (graphic) drawings were reviewed before Item Setup. For the model-based paradigm, a 3D Interactive Viewable (3DIV) was reviewed before Item Setup. For the model-based Purchase Product Definition (PPD), it was decided, based upon the current business processes of using Enovia™ to manage the PPD, to insert the 3D Technical Data Package (TDP) as content within the PPD. Then the PPD could still be managed by Enovia. This is an opportunity to improve the PPD process in future MBE activities. Table 4-2 shows the time collected for the traditional drawing-based approach versus the new MAP-R paradigm approach.

Table 4-2 Prepare for Manufacturing Timing Data.

Traditional Drawing-Based	Model-Based (MAP-R) Paradigm
8.78 hrs	6.56 hrs

4.6.3. Human Factors Data

Human factors data was unable to be collected for this use case.

4.6.4. Activities and Errors

No significant process errors were observed or reported during this use case.

4.6.5. Findings of Note

Both purchase engineer and vendor appreciated the PPD that contained the necessary derivative models and 3DIV to fabricate the model-based MAP-R parts.

This page intentionally left blank.

4.7. Use Case 7: Create Derivative Files for Manufacturing

4.7.1. Description

This use case involved only the model-based process. This use case prepared and validated the necessary intermediate and end derivative models from the source native model for KCNSC's downstream applications.

4.7.2. Drawing-Based and Model-Based Differences

This activity was not performed for the traditional drawing-based activity since no authorized part-defining model was provided. In this case, the authorized part-defining drawing was provided as a 2D static drawing in PDF format, and a STEP AP203 shape model was provided.

For the model-based paradigm, four derivative models were created from the Creo source model. This model was part of the product definition baseline that was authorized in the CER. Two consisted of end derivative models. A Parasolid model and ACIS® model were created as significant downstream applications (e.g., computer numerical control, coordinate measurement machines, simulation analysis) that typically use Parasolid or ACIS as their geometry kernel of choice. Furthermore, a STEP AP203 intermediate derivative model was created as backup also from a Creo export. Each of these were validated using CADIQ to make sure that they were equivalent to the source Creo model. Then a manual certificate with electronic signature was created to confirm this equivalency and was traceable back to the source.

Finally, a 3DIV final derivative model was created with an Anark Core™ workstation. The final derivative model created is primarily for human consumption, it was in the form of a 3D PRC PDF, and it contains both shape and tolerance information. Figure 4-19 illustrates the 3DIV created for the MAP-R project.

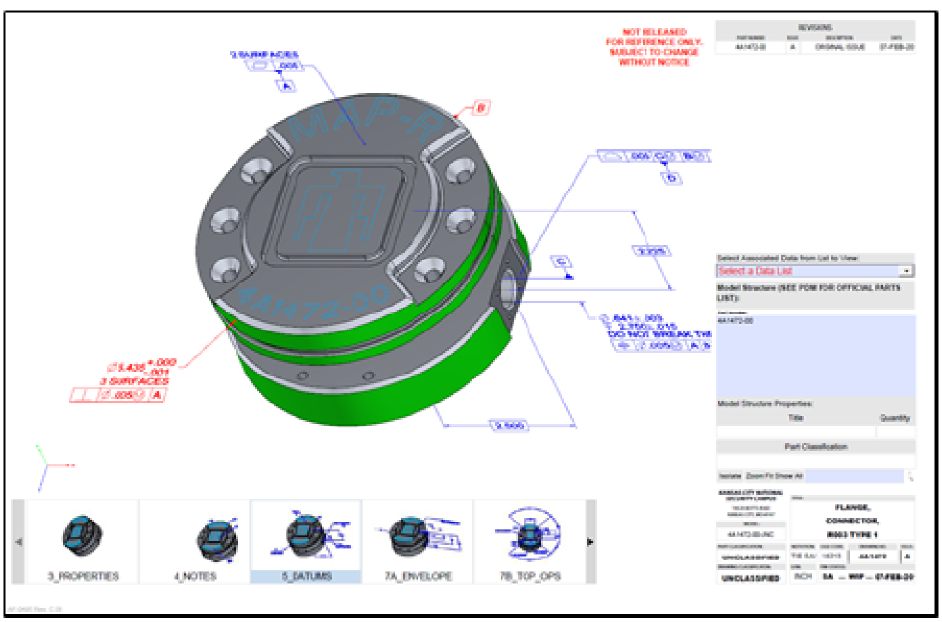


Figure 4-19 MAP-R 3DIV.

Table 4-3 shows the time collected for the traditional drawing-based approach versus the new MAP-R paradigm approach for each released baseline. Two baselines were released.

Table 4-3 Create Derivative Files for Manufacturing Timing Data.

Traditional Drawing-Based	Model-Based (MAP-R) Paradigm
n/a	1.75 hrs

4.7.3. Human Factors Data

Human factors data was unable to be collected for this use case.

4.7.4. Activities and Errors

No significant process errors were observed or reported during this use case.

4.7.5. Findings of Note

This use case was critical towards establishing trust in the part-defining model and contributed toward obtaining MBE Maturity Level 2 – Trusted Model-Centric. Checking the source model (i.e., Creo Native), creating appropriate derivative models, and equivalency validation.

Furthermore, creating the 3DIV was a key component of MBE Maturity Level 3 – Model-Based Definition that was proven an attractive human user experience tool and was received well by all who encountered it.

4.8. Use Case 8: Package Product Definition for Manufacturing

4.8.1. Description

This use case involves the activities associated with preparing a Technical Data Package (TDP) for product realization and product acceptance.

The Department of Defense has relatively recently defined a new standard practice, MIL-STD-31000A, for communicating 3D product data within a technical data package. Many view that a 3D TDP is a key component for model-based enterprise.

A 3D TDP is essentially a package of product and process data elements used for a specific purpose. For the MAP-R project, its purpose was stated as: Contains models and documents that support the fabrication and acceptance of product for the Model Authorized Product Realization (MAP-R) project.

For the MAP-R project, KCNSC created a 3D TDP. This involved using a 3D TDP template, completing the headers information, checking the appropriate product data element boxes, creating a .u3d PDF for the 3D viewable, and then attaching and describing the appropriate TDP elements (e.g., derivative models, 3DIV, certificates).

The resulting 3D TDP involved a .pdf container. This 3D TDP consists of a coversheet and contains 3D TDP elements. Our coversheet contains a header agreed to by the NSE's MBIT community, selection of deliverable data products, other associated items, and a dynamic 3D view of the product. The attachment contains the items declared on the coversheet, and for this instance it included the STEP, Parasolid, and ACIS derivative models and their respective derivative model equivalence certificates.

4.8.2. Drawing-Based and Model-Based Differences

For the traditional drawing-based activity, the current Purchase Product Definition (PPD) served as a limited technical data package. For the MAP-R experience, KCNSC took full advantage of the idea of collecting the appropriate product data elements (e.g., derivative models, 3DIV) within a single technical data package following the NSE MBIT guidelines and KCNSC's implementation. Table 4-4 shows the times allocated to produce a 3D TDP for MAP-R Baseline B and MAP-R Baseline C.

Table 4-4 Produce a 3D TDP Timing Data.

MAP-R Baseline B	2.25 hours
MAP-R Baseline C	2.00 hours

4.8.3. Human Factors Data

Human factors data was unable to be collected for this use case.

4.8.4. Activities and Errors

No significant process errors were observed or reported during this use case.

4.8.5. Findings of Note

Creating a 3D TDP for the purchase product is attractive. It could replace or augment the current practice of a Purchase Product Definition (PPD).

For the future, once our technical data elements are managed and controlled within a part-centric product lifecycle management system, a 3D TDP can be automatically generated based upon a TDP manifest.

4.9. Use Case 9: Manufacture Part

4.9.1. Description

This use case includes all activities that are part of the manufacturing process to include bidding, planning, machining, and then inspecting the part. For MAP-R, these activities were broken into observable chunks for which we could make meaningful comparisons. It must be noted that different manufacturers – Graham and Arundel – were used for the drawing-based (Graham) and the model-based (Arundel) process, and while overall their manufacturing processes were similar, there were idiosyncrasies that made comparing them difficult in terms of workload, and these challenges are discussed. The activities assessed were broken down in the following manner: contract review, engineering analysis, turning, milling, Coordinate Measuring Machine (CMM) and inspections. The differences and similarities of these activities are discussed in detail below.

4.9.2. Drawing-Based and Model-Based Differences

The manufacturing process was broken down into six different activities to allow for comparison across companies. The differences and similarities of these activities are discussed below.

- Contract review – both companies were similar.
- Engineering analysis – for Graham, engineering analysis included building the engineering models used for manufacturing, and each individual machinist filled in the details for their respective machines on the floor. This differed from Arundel where the engineer was responsible for organizing the machining activities, then programmers created the initial programs, and the machinists just ran the machines, for the most part.
- Turning – both companies were similar; however, Graham had the machinists program on the floor at their machines.
- Milling – same as turning.
- CMM – Graham processed CMM at the end of manufacturing but before inspection, and as a finite activity, whereas Arundel included the CMM engineer in the contractual process, and they processed CMM piecemeal over the manufacturing timeline.
- Inspections – both companies were similar.

Also worth noting, and intrinsic to this study, the overall level of technology employed by each company was different. Graham generally used older machines and computers. They did not have their machines integrated into a Wi-Fi network and had to transfer programs with memory sticks or machine specific connectors attached to a computer on a cart. Conversely, Arundel had more modern computers and machines and had them integrated into a Wi-Fi network over which they transferred programs and models. However, the significance of these differences on the results was not apparent either through the ethnographic observations or the workload data.

4.9.3. *Human Factors Data*

4.9.3.1. Workload Models Comparison

This section presents and compares the drawing-based and model-based workload models for each of the sub-activities for this use case and discusses similarities and differences.

4.9.3.1.1. Contract Review

For each of the manufacturers, the beginning of any manufacturing contract involves up-front analysis of the part and the effort required to make it. This data is then used to formulate a bid on the work. For the participating contractors, this involved analyzing all data attached to the Purchase Order and Quality Requirements (POQR) document. For the drawing-based process, this included the 2D drawing of the part and GD&T. Conversely, for the model-based process, the 2D drawing was replaced with a 3D PDF file that provided equivalent information. It is this up-front process that allows the contracting company to decide on the difficulty of the part and subsequently start planning for the work. Figure 4-20 and Figure 4-21 display the workload models for the manufacturing contract review for each of the processes.

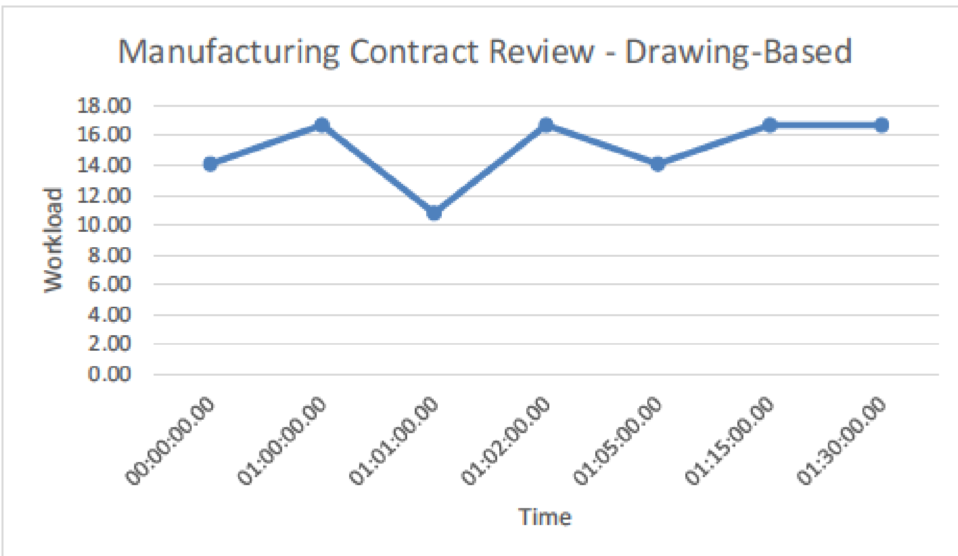


Figure 4-20 Manufacturing Contract Review – Drawing-based Workload Model.

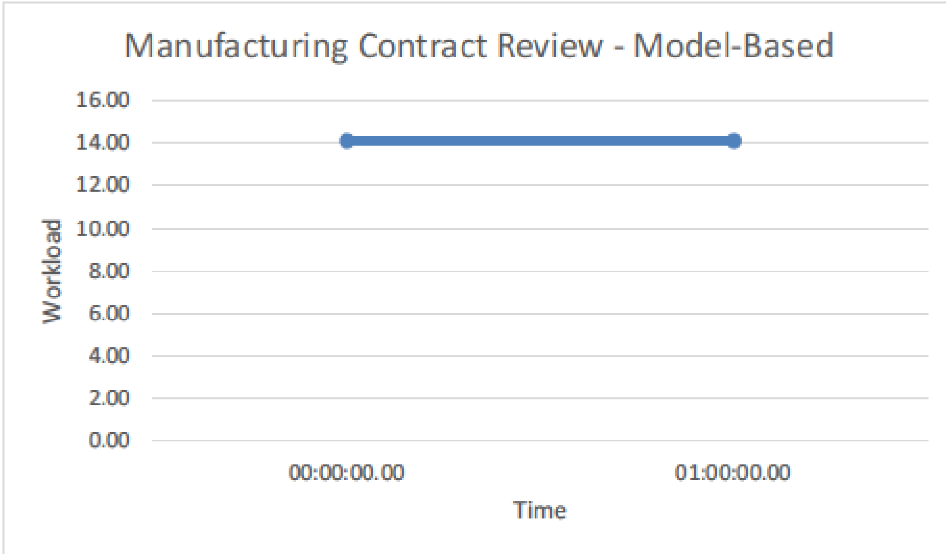


Figure 4-21 Manufacturing Contract Review – Model-based Workload Model.

Figure 4-22 depicts the time in workload levels for this activity.

Time at Workload Level for Manufacturing Contract Review – Drawing

Low	Med	High
0-14	15-18	19 - 21
1:15:00	0:00:00	4:50:00

Time at Workload Level for Manufacturing Contract Review – Model

Low	Med	High
0-14	15-18	19 - 21
2:25:00	0:00:00	0:30:00

Figure 4-22 Time at Workload Levels for Manufacturing Contract Review.

Based on the data collected, the model-based activity took less time-to-complete, and with less time spent in the high workload condition. This is most likely due to including the preliminary modeling work done by the drawing-based manufacturer for this step in the use case. However, it must be noted that these models were constructed based off of interview data, and a more accurate accounting would need to be done to draw any statistical conclusions. However, at least anecdotally, there is a difference between the two processes.

4.9.3.1.2. Engineering Analysis

Once the contract is bid and won, each contractor provides the POQR data to their engineering team. The team then begins to translate the data into working materials and serial operations that are in-line with the company's individual processes, and from which the technicians can begin building the parts. For the contractor completing the drawing-based process, this included analyzing the part, building in-process models, creating setup and measurement sheets, and scheduling machines for each operation. For the model-based contractor, this effort included analyzing the part and creating setup and measurement sheets. They did not complete the in-process model building at this stage, but rather handed the data off to programmers dedicated to creating these models for both the turning and the milling operations, and also developing the schedules. We chose not to include that work here, but rather incorporated it into the turning and milling activities that were analyzed later. Figure 4-23 and Figure 4-24 depict the workload models for this activity for both processes.

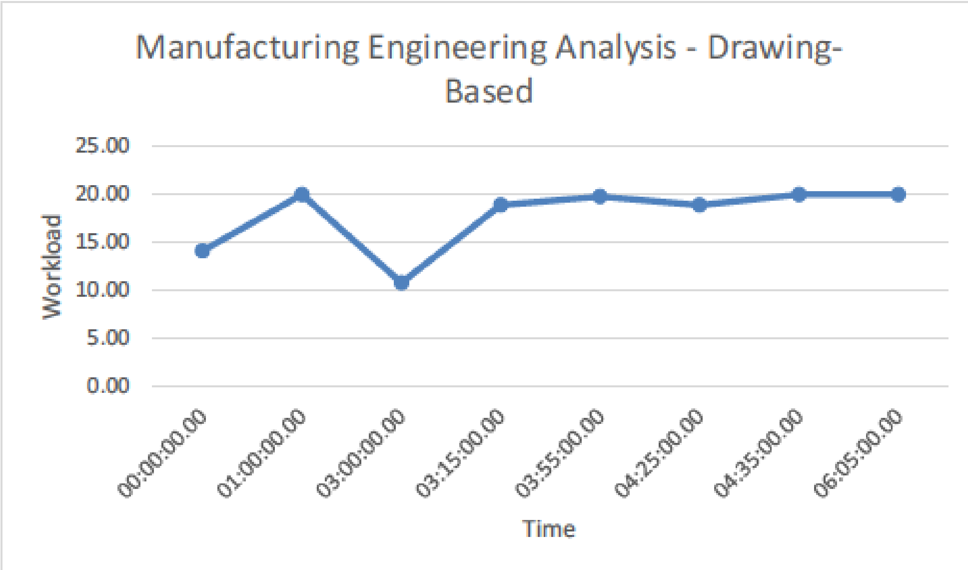


Figure 4-23 Manufacturing Engineering – Drawing-Based Workload Model.

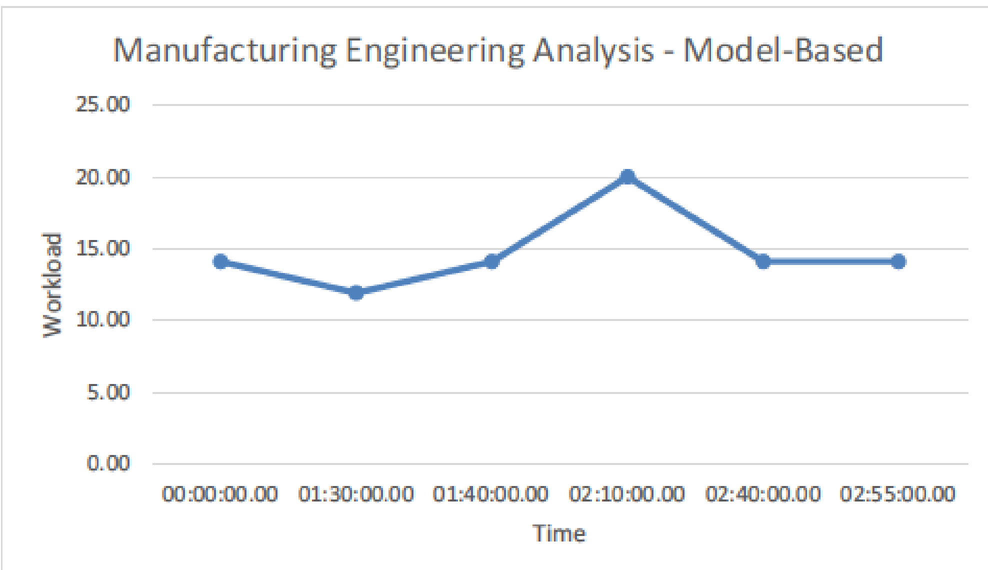


Figure 4-24 Manufacturing Engineering – Model-Based Workload Model.

Figure 4-25 depicts the time in workload levels for this activity.

Time at Workload Level for Manufacturing Engineering – Drawing

Low	Med	High
0-14	15-18	19 - 21
1:15:00	0:00:00	4:50:00

Time at Workload Level for Manufacturing Engineering –Model

Low	Med	High
0-14	15-18	19 - 21
2:25:00	0:00:00	0:30:00

Figure 4-25 Time at Workload Levels for Manufacturing Engineering.

Based on the data collected, the resulting workload models depict a difference in time and workload, with the model-based process showing less time overall to complete, and with less time spent in the high workload condition. This data was also compiled from interviews, therefore statistical analysis is not forthcoming, but anecdotally a difference is apparent. This difference is largely due to the differing processes of the two contractors more than the influence of the process-specific reference materials.

4.9.3.1.3. Turning

For both the drawing-based and model-based processes, the turning activity includes verification of the program, some additional programming, setup of the turning machine, and the actual turning operation itself. Interspersed through the cutting activity, the machinist would make some preliminary measurements, and if changes were needed, the machinist would make them "on-the-fly" and cut/re-cut as necessary. Also, as mentioned previously, a small amount of turning pre-programming was accomplished by the engineer in the engineering review activity for the drawing-based process, but incorporated here in its entirety for the model-based process. This was because the drawing-based machinist did the majority of programming at the machine, and the team endeavored to compare the programming activity for both processes.

Once the program was received by the machinist, both contractors performed turning over two operations. For each contractor, the engineer provided the machinist with a setup sheet, a measurement sheet, and the part reference material. For the drawing-based contractor, this was a printout of the 2D drawing with all GD&T. For the model-based contractor, this was the 3D PDF on a laptop computer with views displaying associated GD&T. There was a difference between the two contractors on how much programming was required at the machine. For the drawing-based contractor, the turning machinist built the program off an older program at the machine. The machinist used reference models for dimensions from the engineering analysis, but then employed a text editor to enter the cut dimensions for the turning machine on a desktop computer on a cart positioned at his workstation. The machinist then transferred the program through that computer to the turning machine using an RS-232 communication cable. This contrasted with the model-based process where the machinist downloaded the pre-built turning program over Wi-Fi to a laptop already at the work location by the cutting machine. The machinist then opened the program on this laptop, verified it, made some minor changes, then transferred it to the cutting machine through Wi-Fi and began cutting. Figure 4-26 and Figure 4-27 depict the workload models for both processes.

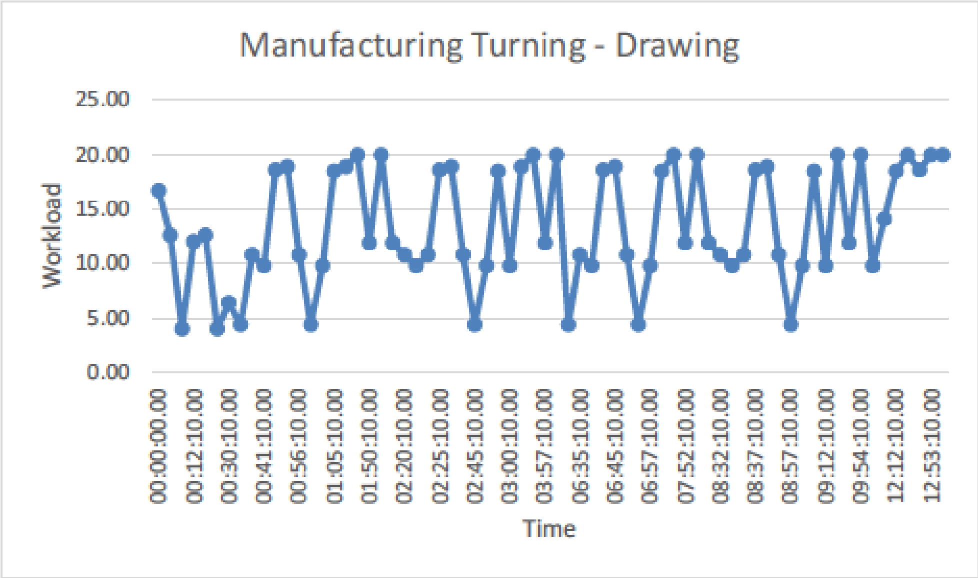


Figure 4-26 Manufacturing Turning – Drawing-Based Workload Model.

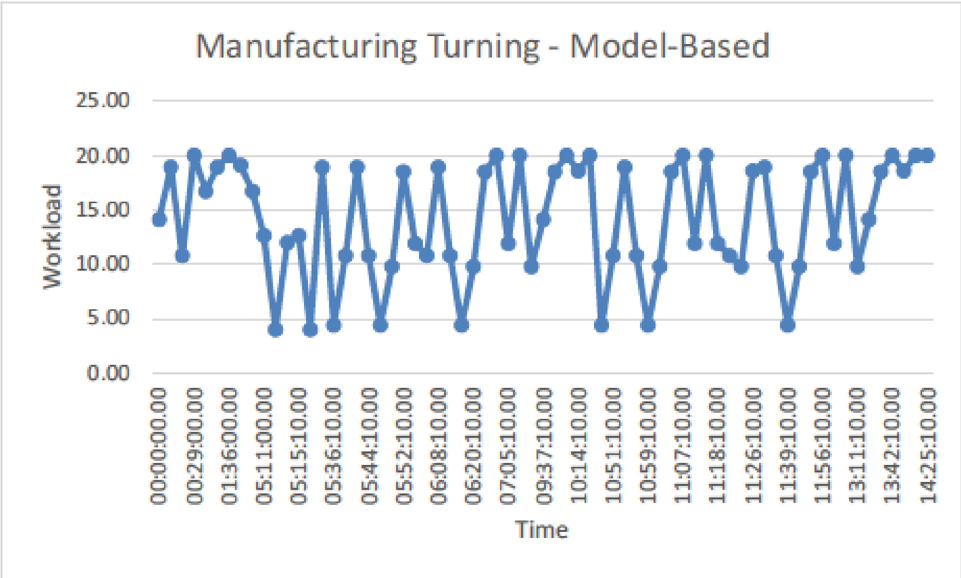


Figure 4-27 Manufacturing Turning – Model-Based Workload Model.

As depicted by the workload models, the model-based contractor's turning activity took longer than the drawing-based process; however, it must be re-stated that the turning pre-programming was included in the model-based process model, and this is the primary cause for the increase in time over the drawing-based process model. More insight into the comparison of the two processes can be gained by comparing the time at workload level totals displayed by Figure 4-28.

Time at Workload Level for Manufacturing Turning – Drawing

Low	Med	High
0-14	15-18	19 - 21
2:50:10	0:10:00	10:23:00

Time at Workload Level for Manufacturing Turning – Model

Low	Med	High
0-14	15-18	19 - 21
2:19:10	0:15:00	11:51:00

Figure 4-28 Time at Workload Levels for Manufacturing Turning.

In addition to the overall turning activity being longer for the model-based process than the drawing-based process, the time spent in the high workload condition was also greater. This again is as expected since, as discussed previously, the model-based process includes the turning pre-programming activity, which is time consuming and cognitively demanding.

4.9.3.1.4. Milling

Similar to the turning activity, for both processes, the milling activity included program verification, some additional programming (varies by process), milling machine setup, and finally cutting and some preliminary measurements. Also, just as described above for the turning activity, the drawing-based process machinist did much of the programming at the machine on a laptop located close to the work area. The machinist began with the initial program created by the engineer and opened it in GibbsCAM® to review it and make modifications. The machinist spent a large amount of time translating the model to the dimensions and formats required for the Computer Numerical Control (CNC) machine and cross-referencing it with the drawing. The machinist ordered a custom tool to cut the small holes in the part, and finally output his modified file into a .txt document and proceeded to modify the .txt document briefly before loading it onto a memory stick and transferring it to a computer that has Wi-Fi and can communicate with the CNC machine to upload it.

For the model-based process, there was much less programming time at the machine, since the model-based manufacturing company did more pre-programming. Also, the model-based company milling machines were attached to a Wi-Fi network and could download files directly from Wi-Fi access points, rather than need to provide a physical connection or a transfer cart. Additionally, any programming at the machine could be done directly through the computer interface attached to the machine, which mimicked a laptop in terms of usability. This contrasted with the drawing-based milling machine where the interface was mostly to run the machine, not for detailed program review. This process had to be done on a separate laptop when needed. Following initial machine programming, for each process, all subsequent activities followed a similar pattern of prepping the machine, getting tools, cutting a part chuck, loading the part, and then sequentially performing the planned cuts as created through the programming process. It is at this point where the two processes differed the least. Figure 4-29 and Figure 4-30 depict the workload models for both processes.

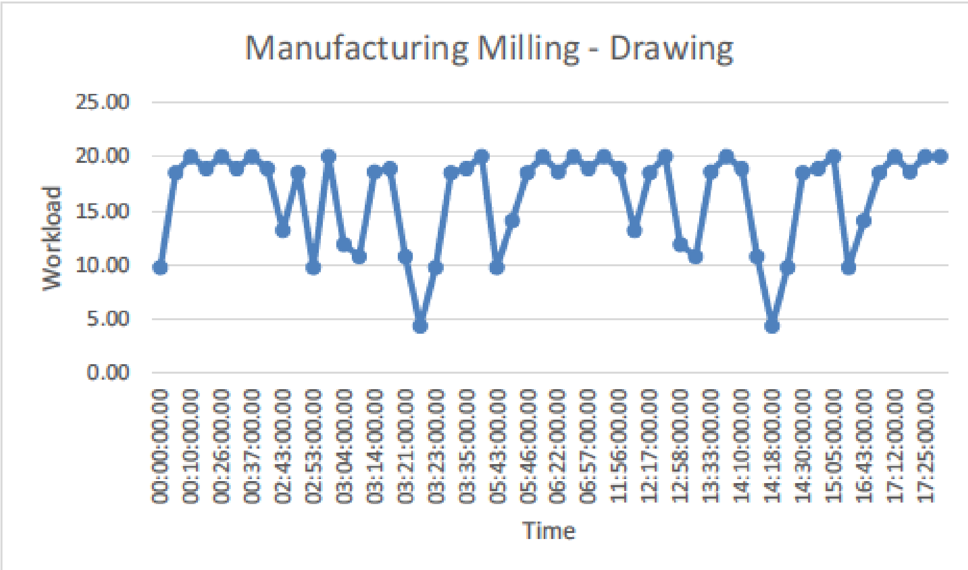


Figure 4-29 Manufacturing Milling – Drawing-Based Workload Model.

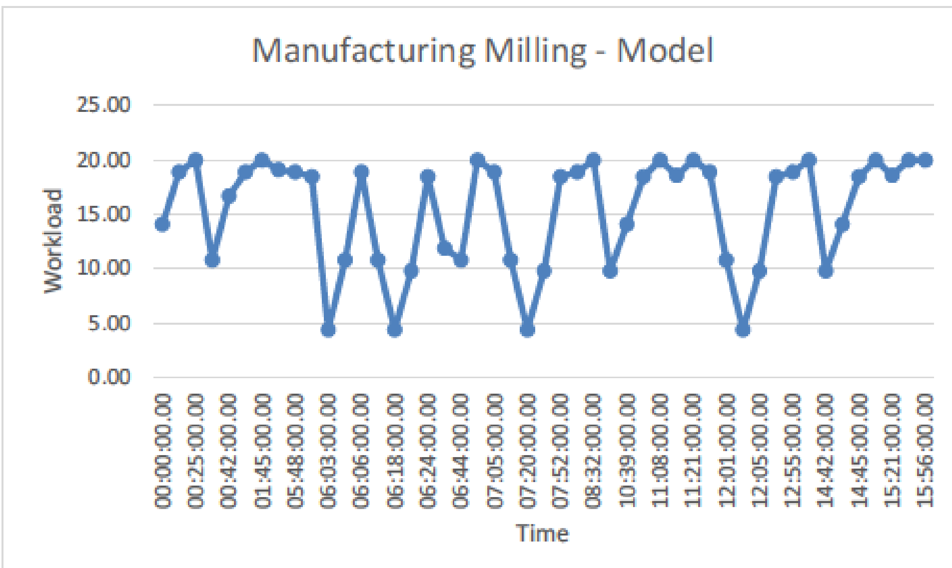


Figure 4-30 Manufacturing Milling – Model-Based Workload Model.

As discussed previously, the two processes differed most in the initial activities involved with setup and programming at the machines. Eventually, the processes became similar and finally ended almost identically as the machinists would close-out the build. Overall, the execution time of the model-based process was shorter than the drawing-based process.

Time at Workload Level for Manufacturing Milling – Drawing

Low	Med	High
0-14	15-18	19 - 21
1:33:00	0:00:00	16:22:00

Time at Workload Level for Manufacturing Milling – Model

Low	Med	High
0-14	15-18	19 - 21
1:43:00	0:15:00	13:58:00

Figure 4-31 Time at Workload Levels for Manufacturing Milling.

Figure 4-31 depicts the time spent in each workload condition, and while both processes have the machinists spending a large portion of time in a high workload condition, the drawing-based process machinist spent more time in the high workload condition than the model-based machinist for this use case.

4.9.3.1.5. Coordinate Measuring Machine (CMM)

Data were collected for the CMM process for both the drawing-based and model-based through interviews and cognitive walkthroughs. Models were constructed based on reported activities by the CMM technologists for both process companies. Figure 4-32 and Figure 4-33 depict these models. There are some differences in the activities reported by the CMM technologists that were captured in the interviews and reflected by the models. Notably, the drawing-based CMM technologist spent more time in the beginning of the process manually setting up the machine and programming the geometry, where the model-based technologist relied more on the digital model. This discrepancy is reflected in the overall execution time. Additionally, the drawing-based technician used Hexagon Manufacturing Intelligence PC-DMIS™ software and the model-based technician used Zeiss CALYPSO® software. Figure 4-32 and Figure 4-33 depict the workload models for the CMM uses case.

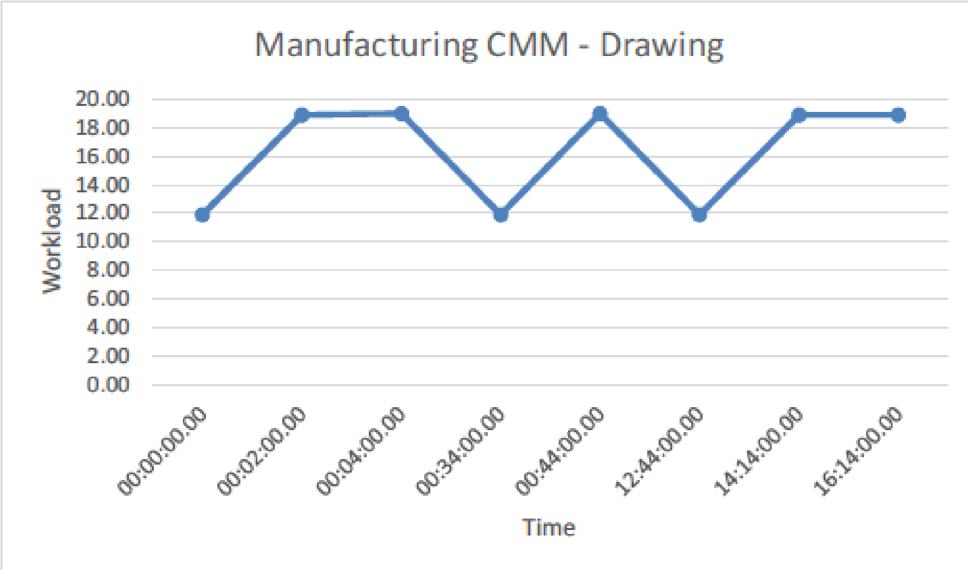


Figure 4-32 Manufacturing CMM – Drawing-Based Workload Model.

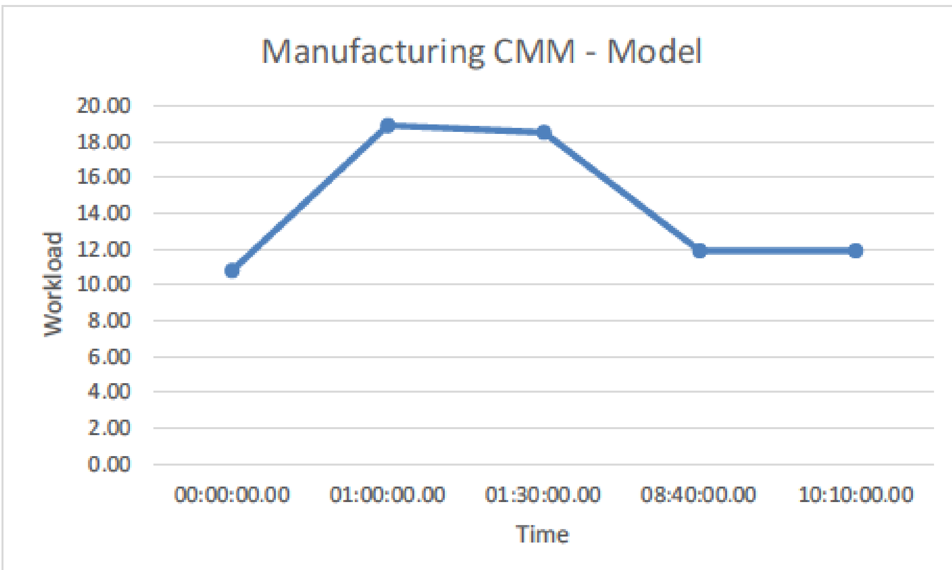


Figure 4-33 Manufacturing CMM – Model-Based Workload Model.

Figure 4-34 details the time at workload level detail for the CMM use case. The CMM technician for the drawing-based process spent more time performing high workload activities than the CMM technician in the model-based process. This was due to the differences in the initial setup activities.

Time at Workload Level for Manufacturing CMM – Drawing

Low	Med	High
0-14	15-18	19 - 21
1:42:00	0:00:00	14:32:00

Time at Workload Level for Manufacturing CMM – Model

Low	Med	High
0-14	15-18	19 - 21
2:30:00	0:00:00	7:40:00

Figure 4-34 Time at Workload Levels for Manufacturing CMM.

4.9.3.1.6. Inspections

There are three inspection activities that occur as part of the manufacturing use case, in-process inspection, first article inspection, and source inspection. Figure 4-35 and Figure 4-36 depict the two in-process inspections. The analysis data for the in-process inspection is incorporated into the turning and milling models for both processes as described previously. The first article and source inspections activities are captured in Section 4.11.

Figure 4-35 Graham In-Process Inspection. (Note drawings are not ITAR they were marked inaccurately by the vendor)

Figure 4-36 Arundel In-Process Inspection.

4.9.3.2. Survey Data

The NASA TLX and SART surveys were administered following observations and interviews for each of the manufacturing activities. However, survey results indicated that none of the activities performed for either of the processes were reported as high workload by the performing individuals. Results from the SART survey agreed with the TLX that the overall level of SA was fairly high while performing all manufacturing activities for both processes.

4.9.4. *Activities and Errors*

Over the course of observations for the turning and milling activities, for both processes, there were a few instances where the turning machinist or the milling machinist had to stop activities and either replace a tool or use a second blank to work out the kinks of the program. These events were not considered errors but merely part of normal operations. There were never any instances of true errors observed for these activities. This may be due in part to the sequential, step-by-step nature of these activities. By completing smaller increments of work and remaining vigilant, the machinists allowed themselves to notice issues, if they arose, and time to correct them before they became unmanageable. No errors or problems were reported by any of the other interviewed engineers or technicians for these processes.

4.9.5. *Findings of Note*

There were a number of interesting anecdotal findings surrounding the observations and comments made for all of the manufacturing activities. These are provided here in context in Table 4-5 and Table 4-6.

Table 4-5 Drawing-Based Manufacturing Process Observations of Interest.

Event	Findings/Comment/Observation
Engineer Interview	Lots of mental spatial referencing needed to program the machine. Need to hold pictures in your head about what the machine is doing. High workload.
Engineer Interview	The engineer will re-create drawings based on the order of operations. Adds dimensions to the sketch. About 10 min for drawing in SolidWorks®, about 20 minutes for dimensioning.
Engineer Interview	Drew a new model for OP30, took about 1 hour to create this OP. Note: It is up to the miller to determine the details of how each part of the OP is performed.
Engineer Interview	For an established part, everything should be fine for a model-only. But when they have started cutting and they make a change, it would be ugly to rely on models only. Changes happen quite often.
Turning OP10 setup	Calculating how to set up the cuts by hand and referring to the drawing many times.
Turning OP10 setup	Inspecting the turning program line-by-line and making minor administrative modifications.
Turning OP10 setup	Using a vertically mounted keypad, mounted on the machine, to type in strings of characters. Not ergonomic.
Turning OP10 setup	Uses the drawing as a reference to make the turning program in the machine. Started with an old program from a different part and modified it for the current part. Did everything in head and hand. High workload here.
Turning OP10 setup	Lots of back and forth between the computer and the drawing to modify the program.
Turning OP10 setup	Does a preliminary check of the program to make sure all parameters are there. Found a small mistake and fixed it.

Event	Findings/Comment/Observation
Turning OP10 setup	Transfers program over RS232 connector between computer and CNC turning machine. Machine needs to be primed to accept the transfer from computer.
Turning OP10 setup	Writes out the rest of the tooling list while looking at drawing. High cognitive load.
Turning OP10 setup	Programmed 20 lines for the first cut and about 20 characters per line, 3 parameters per line. This is done for each cut, so the program is approximately 4x20 lines with repetition.
Turning OP10 setup	Programming at the machine is slow going as the machine interface does not have copy and paste, and this needs to be done multiple times.
Turning OP10 setup	The machinist saw that there was not a clear depiction of the length and angle of the chamfers on a particular section of the part. Had to search the reference sheet extensively.
Turning OP10 setup	Had to stop the program as a tool did not have the length needed to make a cut. Will have to mill a part of the tool structure off.
Turning OP10 setup	Lots of purposeful observations of the machine while it is cutting. Lots of decisions made while the program is running. Needs to stop it periodically to make small adjustments.
Milling OP 30 setup	Created a custom tool that will cut the small holes in the part since the original tool did not have enough clearance.
Milling OP 30 setup	Modifying the program by hand for transfer over to CNC machine. Deleting certain lines that are not needed and removing carriage returns.
Milling OP 30 setup	Programming in GibbsCAM and then converting to a text file to transfer to the CNC machine.
Milling OP 30 setup	Using a computer on a cart that has the program that can communicate with the CNC machine by Wi-Fi to transfer the file.
Milling Op 30 setup	The machinist is adding an orientation to the code for each cut. This information is originally captured as a note, then added into the text file. Ideally, this is a step that could be done automatically but would require an add-on to get it into the file directly. This is done multiple times for the milling program.
Milling Op 30 setup	Uses a 3D scanner to get measurements of tools.
CMM Interview	Need to figure out how to allow for the addition notes to a 3D reference material.

Table 4-6 Model-Based Manufacturing Process Observations of Interest.

Event	Findings/Comment/Observation
First meeting	Was a little harder without the 2D print. Lots of comments about whether there was going to be a print.
VP of Sales Interview	How would we control revs of the 3D PDF?
Engineer Interview	Uses Excel with his own spreadsheet as a tool. Looked at the 3D PDF during the quote. Made the initial judgement on the quote using the 3D PDF (about 30 minutes).
Engineer Interview	The 3D PDF could be better for a quote if some information was provided to help understand features and challenging items.
Engineer Interview	The 3D PDF for the programmers was a little difficult to use since you cannot see all measurements in one shot. You have to page through the views.
Engineer Interview	The way the measurements in the views are laid out is not in line with the manufacturing process.
Engineer Interview	Difficult to open the 3D PDF. Needed Adobe 11 and had to make some setting changes.
Engineer Interview	Opened 3D PDF in Adobe. Noticed how the notes and annotations appeared based on different views. Did not originally see the notes. Work on making the format better, make it look more like a spec sheet.
Engineer Interview	Printed out views from the 3D PDF showing important info and the part in important positions. Used these as a 2D reference sheet.
Engineer Interview	Took about 1 hour to make a 2D reference sheet from the 3D PDF.
Engineer Interview	The chief engineer forced the floor guys to use the 3D PDF.
Engineer Interview	Do not forget to put the image files for etching the model into the 3D PDF.
Engineer Interview	Took about 30-45 minutes to merge the DXF (for etching) with the model.
Turning Programmer Interview	The 3D PDF does not show all the measurements in one view, so had to page through all the views to see all the measurements.
Turning Programmer Interview	Needed to spend a little more time to get familiar with the 3D PDF print.
Turning Programmer Interview	Normally uses the 2D drawing to make notes on for the piece, but could not on the 3D PDF, so the programmer printed it out and made notes on the sheets.
Turning Programmer Interview	Most complicated feature was the groove, but the complication was on the cuts.
Turning Programmer Interview	Will create the measurement reference sheet for the flow of operations. Will make notes on measurements if they deviate on the reference sheet.
Milling Programmer Interview	Printed out some views to use for reference. Liked working with the 3D PDF, was not too bad to get used to. (10 minutes to look at and print).
Milling Programmer Interview	Did not like not being able to mark up the 3D PDF.
Milling Programmer Interview	Likes how the 3D PDF highlights measurements and features when clicked.

Event	Findings/Comment/Observation
Milling Programmer Interview	Wonders why they draw parts with unilateral tolerance, why not draw the reference at the mid-point with + or – tolerance.
Milling Programmer Interview	Uses a printout to work through the in-process inspection sheet. Being able to mark up the 3D PDF would help out a lot. Also, does not save paper since they have to print out more sheets to get all the measurements, rather than one.
Turning OP20	Mixed about the 3D reference. The turning programmer does not like the way the sheet is laid out, however, it is clearer as to where the measurements are pointing to on the part.
Milling OP40	Has not felt like the milling programmer has been slowed down by the 3D PDF, but he did have to train a bit with it. So far, no big deal.
Milling OP50	Likes how the 3D PDF highlights the feature that the measurement is pointing to.
CMM Programmer Interview	Normally uses a highlighter and makes notes to review the spec. Likes the 3D PDF. Will be a process. Will get a second monitor with 3D PDF. A concern is how to monitor progress since the CMM programmer normally uses the spec sheet to mark off measurements as done. How can we make it so that the 3D PDF can be written on or modified?
CMM Programmer Interview	Spent 1 hour with it. Very intuitive and the help features are easy to use.
CMM Programmer Interview	Taking notes is important to the process. If the part had more features it would be very difficult to not use a paper-based sheet to mark progress.

4.10. Use Case 10: Prepare for Inspection

4.10.1. Description

This use case includes the process planning activities associated with the quality engineer planning for product acceptance by inspection. The Prepare for Inspection use case started with a KCSNC process meeting involving the process, purchase, and quality engineers. Since the MAP-R parts were to be treated as War Reserve (WR) product, and it was determined to be purchased product, a POQR was created from the product definition. The POQR included the following elements:

- Supplier Quality Program requirement
- Calibration/Testing Specifications
- Certification Type
- Other Quality Requirements
- Packaging
- In Process / Source Inspection
- Buyer Information

Some noteworthy content came from the POQR. The seller shall provide dimensional inspection data for all features on 100% of the parts. A supplier CMM program was approved to measure a minimum of 37 different product characteristics.

Activities for this use case involved reviewing product requirements and establishing suitable acceptance methods for both parts. This includes determination of the required quality system level of the selected vendors, as well as an examination of the available inspection equipment.

- Quality documentation and inspection requirements were outlined and relayed to the suppliers through the Purchase Order (PO).
- The KCNSC quality engineer documented the acceptance method for each requirement and prepared the Inspection Instruction in Solumina®. A data package was also created, which collected all required drawings and documents for inspection use (addendum index).
- In order to expedite the inspection process, it was decided to utilize supplier inspection equipment and KCNSC source inspectors to perform inspection activity. This allowed us to avoid heavy work load queues in KCNSC.
- The methods for inspection were selected by the KCNSC quality engineer, relying heavily on CMM due to complex GD&T features on the designs, to ease capturing variables data.
- Acceptance methods were reviewed for compliance with the required Test Accuracy Ratio (4:1). Inspection methods were kept as close to equivalent as possible between the two vendors.

4.10.2. *Drawing-Based and Model-Based Differences*

The traditional drawing process parts were fabricated at Graham. The CMM used at Graham was not accurate enough to inspect certain tolerances on the product, so a deviation was written to account for this deficiency. The CMM at Graham does not have scanning capabilities like the one used at Arundel.

Creating the drawing-based inspection plan involved using drawing highlighting tools that identify inspection methods for each inspection requirement (i.e., product characteristic). See Figure 4-37. As expected, this software tool was not available for the model-based 3DIV.

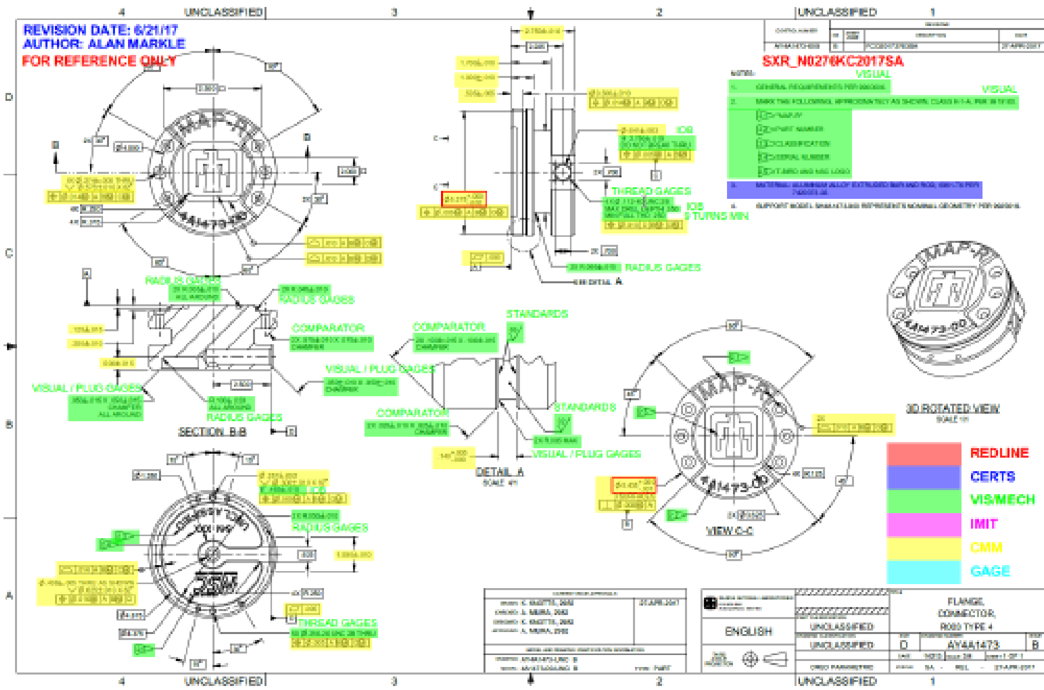


Figure 4-37 Drawing-Based Inspection Plan Methods - Tool Highlighting.

Table 4-7 shows the time allocated to prepare for inspection. This is a bit skewed on the drawing-based time as during the drawing-based fabrication it was determined that KCNSC's receiving inspection would not be performed in a timely fashion. The decision was to perform source inspection.

Table 4-7 Prepare for Inspection Timing Data.

Traditional Drawing-Based	Model-Based (MAP-R) Paradigm
66.98 hours	23.89 hours

4.10.3. *Human Factors Data*

Human factors data was unable to be collected for this use case.

4.10.4. Activities and Errors

One Specification Exemption Release (SXR) was based upon the inability for one of the vendors to have access to an inspection method that complied to the required 4:1 test accuracy ratio.

4.10.5. Findings of Note

Observations from the KCNSC Quality Engineer include the following:

It was important that the team found significant product definition issues previously unknown to the enterprise. The team received good responses from all of those who saw and used a 3DIV. Quotes included:

- *I like it, I like it a lot.*
- *It's about time!*

Additionally, the KCNSC Quality Engineer identified an opportunity for the MBE Quality activity to include the automated creation of a Bill of Characteristics (BoC) and inspection planning function. This could potentially reduce the QE time to generate and document inspections plan by 30%-60%.

This page intentionally left blank.

4.11. Use Case 11: Inspect Part

4.11.1. Description

The two inspection activities addressed in this use case include the first article inspection and the source inspection. Both activities are conducted at the supplier site and are very similar within and between both the drawing-based and model-based processes. The primary difference between these activities, within each process, is when they are performed and who is performing the inspection.

The first article inspection is performed by the supplier, using supplier equipment. The source inspection is performed second by a KCNSC inspector, using KCNSC equipment. They both start with the inspector reviewing the measurement sheet. For the first article inspection, the inspector measures all indicated features. This differs from the source inspection, where the inspector selects a group of measurements (some indicated by the customer, and some at their discretion) to analyze. They then both perform their measurements on a sample of parts to confirm that they are within specification of the design. Note that source inspectors have at their disposal the results of the first article inspection and make it a point to know how the first article inspector performed their measurements. They then try to duplicate the results and also sometimes perform them in an alternate way to ensure accuracy.

Any issues discovered by the first article inspection will necessitate a change to the manufacturing procedures and subsequent re-run of parts if needed. Any issues discovered by the source inspector may require full rework but this is extremely rare, since by the time the source inspection is performed, the part(s) has been through two other inspections and most likely any issues will have been caught and remedied at that time.

4.11.2. Drawing-Based and Model-Based Differences

As discussed previously, there were little if any true differences between the drawing-based and model-based process first article inspections other than the reference material used for the process.

- At Graham, the inspector utilized the Solumina plan and the drawings from the addendum index to review CMM data and inspect other features.
- At Arundel, the inspector utilized the Solumina plan and the 3DIV from the addendum index to review CMM data and inspect other features.

This is reflected by the workload models displayed in Figure 4-38 and Figure 4-39 and is primarily due to the inspectors performing their activities in a very similar fashion. That is, they would create a table of measurements from the reference materials, regardless of the type, and use that table as the primary reference for their inspection activities. They did consult the reference materials to understand the nature of the features they were measuring, but this did not impact time for the model.

4.11.3. Human Factors Data

4.11.3.1. Workload Models Comparison

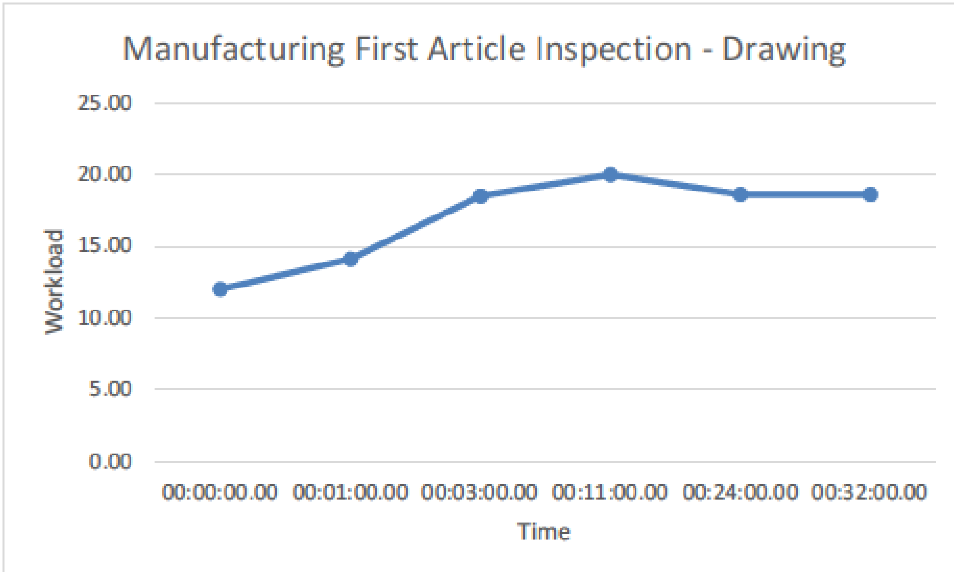


Figure 4-38 Manufacturing First Article Inspection – Drawing-Based Workload Model.

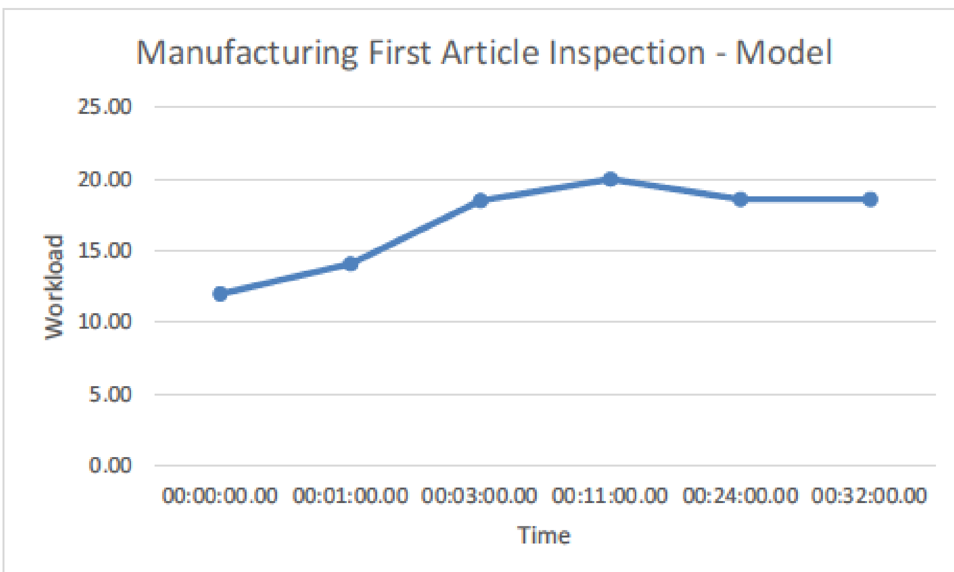


Figure 4-39 Manufacturing First Article Inspection – Model-Based Workload Model.

The lack of differences between the two processes for this use case are also reflected in Figure 4-40 for time at workload level.

Time at Workload Level for Manufacturing First Article Inspection – Drawing		
Low	Med	High
0-14	15-18	19 - 21
0:03:00	0:00:00	0:29:00

Time at Workload Level for Manufacturing First Article Inspection – Model		
Low	Med	High
0-14	15-18	19 - 21
0:03:00	0:00:00	0:29:00

Figure 4-40 Time at Workload Levels for Manufacturing First Article Inspection.

Figure 4-41 and Figure 4-42 depict the two first article inspections.

Figure 4-41 Graham First Article Inspection (note use of drawing).

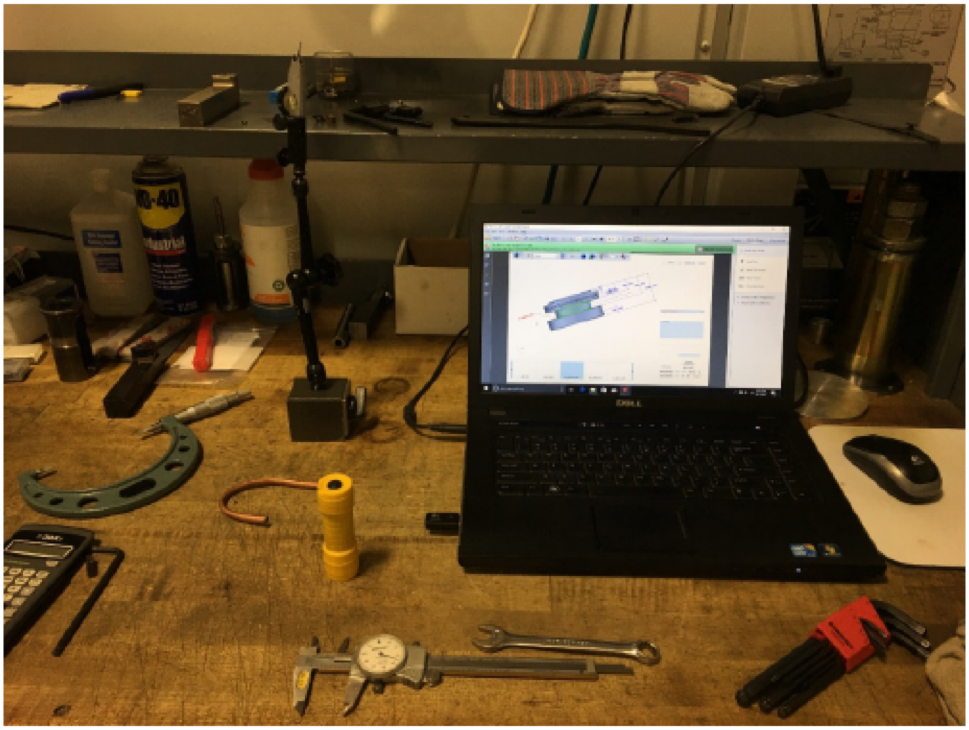


Figure 4-42 Arundel First Article Inspection (note use of 3DIV).

In much the same way, the source inspection did not differ greatly between the drawing-based and model-based processes; however, there is a small discrepancy in time to perform the early setup activities, where the model-based inspector spent a little more time orienting to the 3D PDF to analyze features. Figure 4-43 and Figure 4-44 provide the details.

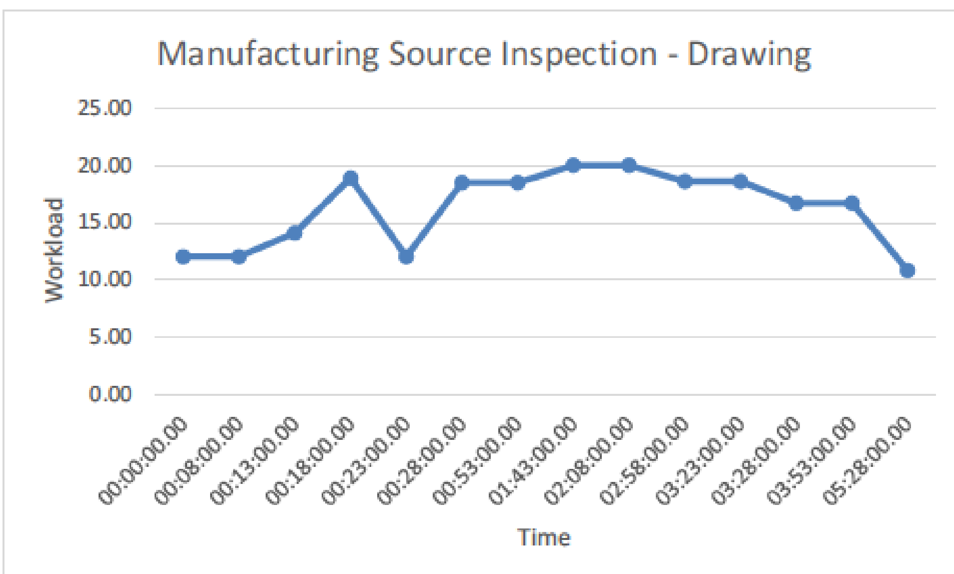


Figure 4-43 Manufacturing Source Inspection – Drawing-Based Workload Model.

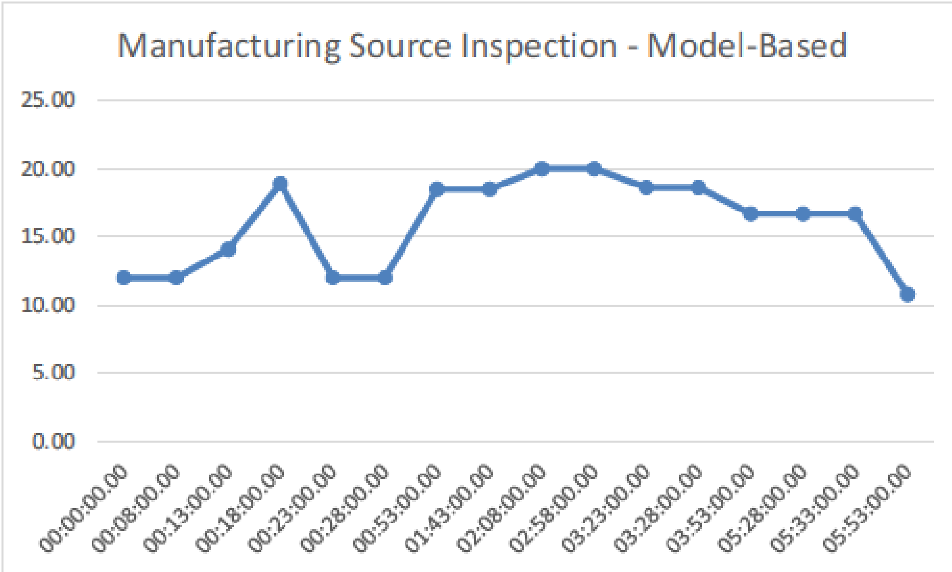


Figure 4-44 Manufacturing Source Inspection – Model-Based Workload Model.

As discussed earlier, there was a minor difference between the two processes concerning the performance of the source inspection. This difference was apparent in the model-based process, and while not affecting the time the inspector spent in the high workload condition, it did affect overall time slightly in the low workload condition. See Figure 4-45 for more detail.

Time at Workload Level for Manufacturing Source Inspection – Drawing

Low	Med	High
0-14	15-18	19 - 21
0:28:00	2:00:00	3:05:00

Time at Workload Level for Manufacturing Source Inspection – Model

Low	Med	High
0-14	15-18	19 - 21
0:53:00	2:00:00	3:05:00

Figure 4-45 Time at Workload Levels for Manufacturing Source Inspection.

4.11.3.2. Survey Data

The NASA TLX and SART survey data did not uncover any significant workload or situation awareness issues for either of the inspection activities for either of the processes.

4.11.4. Activities and Errors

For both processes, no errors were observed or reported by the inspectors for either activity.

4.11.5. Findings of Note

There were a few small anecdotal findings in the form of comments made by the inspectors, which are captured in Table 4-8.

Table 4-8 Inspect Part Comments.

Event	Findings/Comment/Observation
Source Inspector Interview (Drawing-based)	It was difficult to measure the large pass-through hole. Eventually used a cylinder and measured the depth.
First Article Inspector Interview (Model-based)	Might be easier with the 3D PDF to visualize complicated features. Could be a time saver to find all the challenging features of a part.
First Article Inspector Interview (Model-based)	Normally uses the print as the inspections master, but will now have to figure out how to use the 3D PDF for this.
First Article Inspector Interview (Model-based)	Adds the measurements right off the print into the report. Writes measurements down on print, then adds to report.
First Article Inspector Interview (Model-based)	Would probably print out all views. It is hard to not use a print and keep it all digital.

4.12. Use Case 12: Request Product Change

4.12.1. Description

This use case involves the activities associated with requesting a product change. Product change requests were not preplanned but happened naturally for both the traditional drawing-based and model-based paradigm. On both definition sets, an Engineering Authorization (EA) product change was initiated to correct a transcription error in the product definition.

4.12.2. Drawing-Based and Model-Based Differences

For the traditional drawing-based paradigm, the practice is often to create an Advanced Change Order (ACO). This allows the PA to continue work without having to update and release the drawings. The ACO acknowledges what the changes will be and is used in conjunction with the released issue of the drawing, thus becoming the current definition.

Note: The ACO only contains textual description of the changes, and those changes must be completed and released within 90 days of the release of the ACO.

For the new model-based paradigm, utilizing the ACOs was not possible. The model definition relied on the model and its encapsulated data. Therefore, a Final Change Order (FCO) was used. The changes to the model (definition) were competed and released with the FCO. See Table 4-9 and Table 4-10 for more detail.

Table 4-9 KCNSC Change Order Timing Data.

Traditional Drawing-Based	Model-Based (MAR-R) Paradigm
0.58 hours	0.99 hours

Table 4-10 KCNSC Exception Reporting Timing Data.

Traditional Drawing-Based	Model-Based (MAR-R) Paradigm
2.57 hours	0.65 hours

4.12.3. Human Factors Data

Human factors data was unable to be collected for this use case.

4.12.4. Activities and Errors

No significant process errors were observed or reported during this use case.

4.12.5. Findings of Note

SNL creates and manages its EAs (product change system) in a separate IT system disconnected from the Product Data Management system that is used to configure manage drawings, models and MLs. For both definition sets, the engineer was required to enter the change information twice: enter the change into the PDM system so the affected objects could be revised, and then enter the change into the SNL EA Web tool to create the EA.

4.13. Use Case 13: Create Quality Assurance Inspection Procedure (QAIP)

4.13.1. Description

This use case includes the activities associated with preparing and conducting a simulated QAIP with the NNSA site office's quality engineer and inspector, along with the KCNSC quality engineer and inspector.

The QAIP inspection is performed in much the same way as the source inspection; however, it is performed by National Nuclear Security Administration (NNSA) representatives after receiving the parts at the customer site. Much like the source inspection, the QAIP inspector receives a report on what and how the part was measured by the previous inspector (in this case the source inspector) and often tries to measure the part in a different way to ensure validation of results. It must be noted that there are some administrative activities associated with the QAIP prior to and following the actual inspections that were not included in this analysis because of the limited usage of the reference materials in those activities. Furthermore, the QAIP typically only includes a partial inspection.

- Kansas City Field Office (KCFO) inspection of KCNSC inspected product
- Both parts were reviewed and approved by KCFO inspectors using similar methods

4.13.2. Drawing-Based and Model-Based Differences

Overall the QAIP took the same amount of time to accomplish for each process, with similar activities performed for each. However, it was noted that the drawing-based process activities were slightly higher in workload due to the report of increased difficulty in discerning certain measured features while using the drawing reference materials. This difference is reflected in Figure 4-46 and Figure 4-47.

KCNSC time for supporting the QAIP and NNSA's time performing the QAIP is shown in Table 4-11:

Table 4-11 KCNSC QAIP Timing Analysis.

Traditional Drawing-Based	Model-Based (MAP-R) Paradigm
10.00 hours	9.00 hours

4.13.3. Human Factors Data

4.13.3.1. Workload Models Comparison

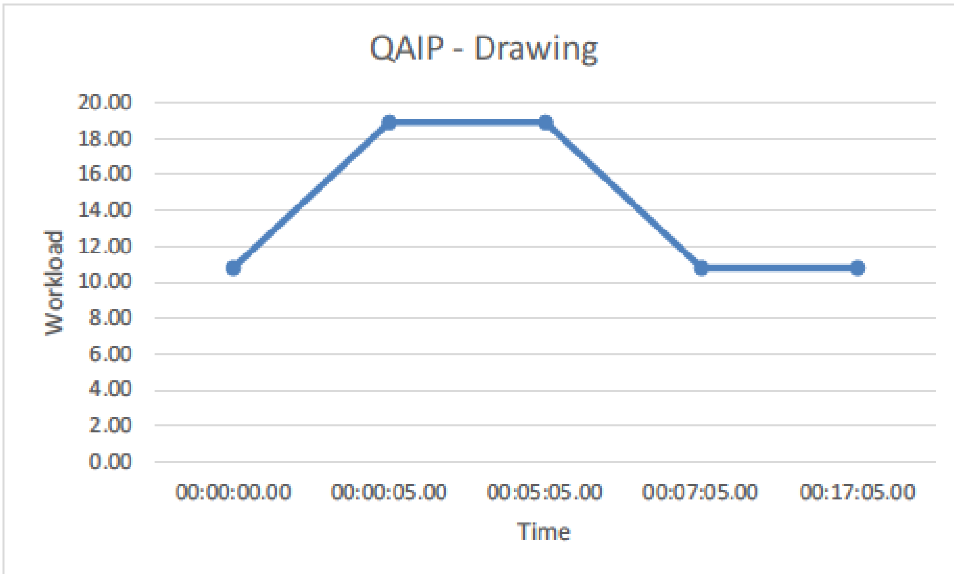


Figure 4-46 QAIP – Drawing-Based Workload Model.

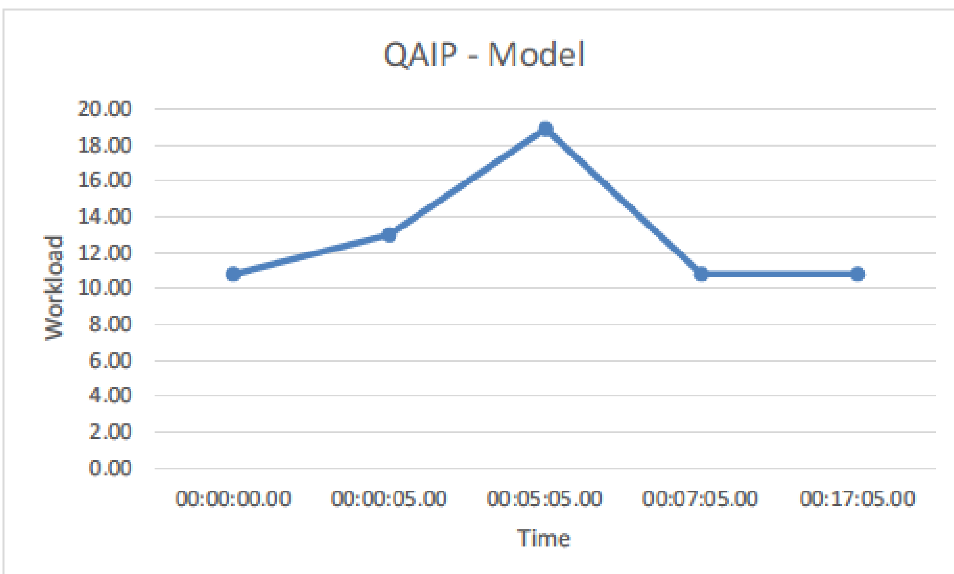


Figure 4-47 QAIP – Model-Based Workload Model.

The difference in difficulty described earlier is also reflected by the time spent in the high workload condition for the drawing-based process in Figure 4-48.

Time at Workload Level for QAIP – Drawing

Low	Med	High
0-14	15-18	19 - 21
0:10:05	0:00:00	0:07:00

Time at Workload Level for QAIP – Model

Low	Med	High
0-14	15-18	19 - 21
0:15:05	0:00:00	0:02:00

Figure 4-48 Time at Workload Levels for QAIP.

4.13.3.2. Survey Data

Survey data was not able to be captured for the QAIP activities due to time constraints.

4.13.4. Activities and Errors

No errors were observed or reported for the QAIP activities for either process; however, there was some difficulty observed for the model-based process involving initial setup of the computers used for inspection to display the 3D PDF correctly. This was noted as an issue with the facility Information Technology (IT) infrastructure, and as such, the time to remedy was not recorded in the model since it is expected that these events were idiosyncratic in nature and ultimately not relevant to the study.

4.13.5. Findings of Note

At the start of the project, the team determined that if NNSA could not execute the Quality Assurance Inspection Procedure (QAIP) using the model-based definition there would be a significant reduction in the business value of the model-based paradigm. However, the study data indicates that NNSA can utilize a model-based part centric definition in their QAIP with no significant impact on the process execution time. There were a few comments of note made by the NNSA inspectors during the QAIP activities that reflect the differences between the drawing-based and model-based reference material. These are reflected below:

- *I liked how the 3D model area* [i.e., 3DIV face] *was highlighted when you clicked on the drawing requirement* [i.e., tolerance annotation]. *It made it very obvious what feature was to be measured.* [Voiced as a means to make finding features easier for inspectors.]
- *The lack of computer access in KCNSC's receiving inspection area.* [Voiced as a concern for using the 3D PDF at the Kansas City National Security Campus (KCNSC) where the QAIPs are executed.]
- *I felt like the 3D drawing (i.e., 3DIV) gave you more detail.* [Voiced as an opinion on the utility of the 3D PDF.]

Based on these comments, it would seem that using the 3D PDF would warrant better performance for QAIP activities, provided that the infrastructure is in-place to allow for the inspectors to utilize it.

4.14. Use Case 14: Perform Engineering Analysis

4.14.1. Description

This use case includes the activities associated with performing an engineering analysis for a specific issue.

Because the model-based MAP-R paradigm found a thin wall issue, the team decided to perform an engineering analysis on that area of interest.

4.14.2. Drawing-Based and Model-Based Differences

For the 4A1473 traditional drawing-based, a drawing and STEP model was provided to perform the analyses. For the 4A1472 model-based MAP-R paradigm, a 3D TDP was used, which included the ACIS derivative model and 3DIV.

4.14.3. Human Factors Data

Human factors data was unable to be collected for this use case.

4.14.4. Activities and Errors

No significant process errors were observed or reported during this use case.

4.14.5. Findings of Note

The 4A1472, model-based MAP-R paradigm analysis was able to use the ACIS derivative model, directly eliminating the re-creation and prep of the STEP model. Table 4-12 shows the time collected for the traditional drawing-based approach versus the new MAP-R paradigm approach.

Table 4-12 Engineering Analysis Timing Data.

Traditional Drawing-Based	Model-Based (MAP-R) Paradigm
50 hours (31.5 model prep; 18.5 analyzing)	12.2 hours

This page intentionally left blank.

4.15. Overall Workload Analysis Results

In answer to our hypothesis for this study, the team set about to determine, through the creation of workload models of our analyzed use cases, which of the two processes, drawing-based or model-based, required the task performers to spend more time in a high workload condition. The summary of results for all workload level data from our models, as depicted in Figure 4-49, clearly demonstrates that the model-based process required the process participants to spend less time in a high workload condition. In order to communicate this finding accurately though, we must acknowledge two caveats to this data as described below.

First, not all use cases were modeled. This was due in part to time constraints and also by determining that certain use cases, by their nature, would warrant more activity with the reference materials than others. Therefore, these use cases were of greater importance and relevance to the workload modeling analysis than the others. Thus, the times displayed below should not be considered representations of the overall execution time for both processes, just the time captured for the use cases analyzed by the workload models.

Second, the times displayed in Figure 4-49, in some cases, do not represent the entire time spent performing the use cases analyzed either, but rather the time spent while performing activities for each use case, directly related with using the reference materials for each process.

Total Execution Time	
Drawing-based	Model-based
89:23:14	83:50:11

Time in Low Workload	
Drawing-based	Model-based
19:56:31	18:22:28

Time in Med Workload	
Drawing-based	Model-based
5:24:38	12:08:38

Time in High Workload	
Drawing-based	Model-based
64:02:05	53:19:05

Figure 4-49 Workload Model Total Time at Workload Level.

Ultimately, the workload analysis set out to answer the question of which process (2D versus 3D) is higher in cognitive workload, and did successfully collect data that allowed us to, at a rudimentary level, answer that question. As discussed in Section 6, Conclusions, the team recommends that a more focused experiment be conducted to allow for a more accurate look at which reference material affords better performance with spatial reference activities as is expected for many of the use cases in the end-to-end design and manufacturing process.

5. FOLLOW-ON ACTIVITIES AND NEXT STEPS

5.1. Integrate lessons learned in current Life Extension Program(s)

The primary follow-on activity resulting from the MAP-R project is to develop an action plan to take lessons learned from MAP-R and integrate them into current Life Extension Programs (LEPs). At the writing of this document, the W80-4 LEP is the next logical candidate program to utilize model-based definition advancements. The team has recommended the use of a part-centric, CAD-driven product structure to generate the ML and the use of a 3DIV as the AY graphic. Figure 5-1 shows ML and 3DIV examples.

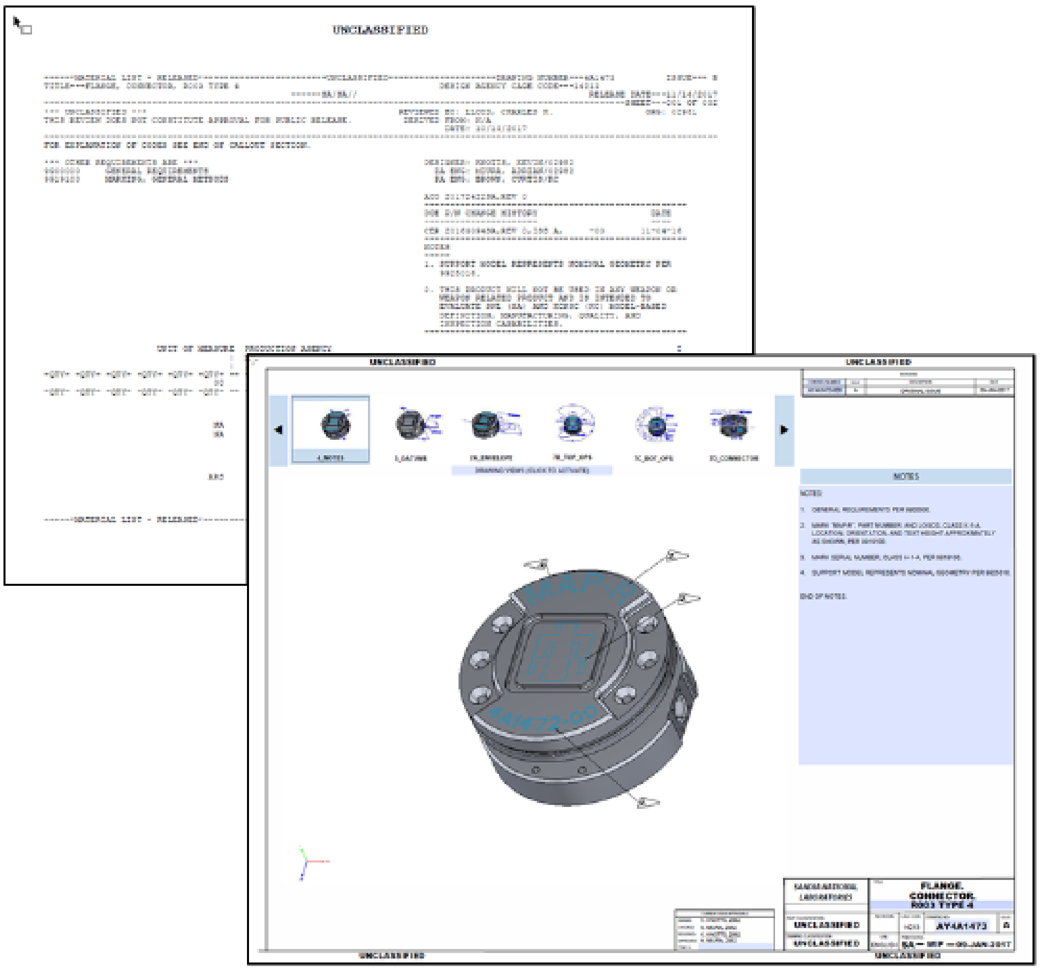


Figure 5-1 ML and 3DIV Examples.

5.2. Experimental Data

Although a wide variety of methods were employed to evaluate the MAP-R processes using either drawing-based or model-based reference materials, the fact that different vendors executed the processes makes any findings from this study anecdotal. While some literature suggests significant cost and time savings by shifting design and manufacturing processes from drawing-based to model-based, no published work has directly compared and examined the different reference materials with respect to operator performance, operator cognitive workload, and usability for the design and manufacture of products.

Experimental data is recommended to advance the NSE's ability to scientifically quantify the differences between the current drawing-based (2D reference materials) process and the future model-based (3D reference materials) process. Specifically, an experiment should be designed to directly compare and quantify the differences between 2D and 3D reference materials with respect to operator tasks requiring use of these materials. Factors that could be measured to assess reference material use are performance (based on success of task completion and time-to-complete), cognitive workload, and usability. The findings of such an experiment could provide quantifiable differences between the reference materials, which may inform several activities, including considerations for reference material composition, operator training requirements, and work task design.

6. CONCLUSIONS

When the team combined the timing data in Table 6-1 with the human factors timing data, the two processes did yield differences, from a time-on-task perspective. The model-based definition process indicated a significant time savings in many cases. In addition, having access to a trusted single source of the definition proved to be very useful to ensure the PA received the correct information. The current drawing process required hand transcription of information at every step. As noted from the body of research, this will most likely result in higher administrative error rates, rework, and ultimately schedule delays.

Table 6-1 Combined Use-Case Timing Data.

HFE Reviewed Use-Cases	89.38	83.83
Non-HFE Reviewed Use-Cases	153.90	69.47
Total	243.28	153.31

Models allow the analysis of things that humans do not readily see. The model-based definition for 4A1472-00 afforded the opportunity to analyze the definition early in the design cycle and identify manufacturability issues. Drawing-based design reviews in many cases are limited to what is visually presented to the team. As identified in the workload modes (Certify Product Definition), this process maintains a high cognitive load throughout the review activities. Utilizing model-based tools to augment the team's ability to identify and correct issues could result in a significant reduction in design and manufacturing issues.

At the time the study was executed, PTC, the vendor for the CAD modeling package, had recently released its STEP AP242 export capability. This first attempt at releasing the standard lacked the ability to export the product and manufacturing data (PMI) as "computer readable" or semantic information. Being able to export this data and display it in an intermediate/natural format will further the concept of a single source from which derivative content can be generated without human translation and its associated delays and errors.

In summary, the NSE is committed to an MBE Transition as evident of a new NNSA Model-Based Enterprise Transition – Initiative (MBET-I) project. An MBE Maturity Index framework has been updated and content proposed. SNL/KCNSC conducted NSE's first authorized part defining model (i.e., NO 2D static drawing).

This MAP-R project confirms that products can be realized and accepted from an authorized part-defining model. This project also demonstrated that a QAIP of a product can be conducted from an authorized part-defining model and showed that the team can be more responsive to change. Furthermore, based upon human factors, the shifting of cognitive load resulted in a reduction of mistake opportunities. The project identified some quality engineering improvement opportunities and new areas to explore. Finally, the MAP-R experience was most positive to pursue significant MBE insertion opportunities within the W80-4 and future WR programs.

This page intentionally left blank.

REFERENCES

Alexander, I. F., & Maiden, N., (Eds.) (2004). Scenarios, stories, use cases through the systems development life cycle. New York, NY: Wiley.

Blomberg, J., Burrell, M., & Guest, G. (2003). An ethnographic approach to design. In J. A. Jacko and A. Sears (Eds). *The Handbook of Human-Computer Interaction Handbook: Fundamental, Evolving Technologies and Emerging Applications*. Mahwah, N

Cain, B. (2007). A review of the mental workload literature (pp. 4-1 - 4-32). Toronto, Canada: Defence Research & Development.

Endsley, M. R. (1995). Toward a Theory of Situation Awareness in Dynamic Systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 37*(1), 32-64.

Fetterman, D. M. (1998). *Ethnography: Step by step, Second Edition*. Sage, Thousand Oaks, CA.

Grudin J.T. (1983) Error Patterns in Novice and Skilled Transcription Typing. In: Cooper W.E. (eds) Cognitive Aspects of Skilled Typewriting. Springer, New York, NY

Hackos, J.T., Redish, J.C. (1998). *User and Task Analysis for Interface Design,* John Wiley & Sons, Inc.

Hart, S. G. & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock and N. Meshkati (Eds.) Human Mental Workload. Amsterdam: North Holland Press.

Hedberg, T.D, Lubell, J., Fischer, L., Maggiano, L., Feeny, A.B. (2016). Testing the Digitial Thread in Support of Model-Based Manufacturing and Inspection. *ASME Journal of Computing and Information Science in Engineering*, 16(2). doi: https://dx.doi.org/10.1115/1.4032697

Judkins, T. N., Oleynikov, D., & Stergiou, N. (2008). Enhanced Robotic Surgical Training Using Augmented Visual Feedback. *Surgical Innovation, 15*(1), 59-68. doi: https://doi.org/10.1177/1553350608315953

Kirwan, B. & Ainsworth, L. K. (1992). *A Guide to Task Analysis*, London: Taylor and Francis. A text book that contains various task analysis techniques and their use in the systems engineering process.

W Lazonder, Ard & Biemans, Harm & Wopereis, Iwan. (2000). Differences between Novice and Experienced Users in Searching Information on the World Wide Web. Journal of the American Society for Information Science and Technology. 51. 576-581. Doi: 10.1002/(SICI)1097-4571(2000)51:6<576::AID-ASI9>3.0.CO;2-7.

Lewis, C., Polson, P.G., Wharton, C., & Rieman, J. (1990). Testing a walkthrough methodology for theory-based design of walk-up-and-use interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '90), Jane Carrasco Chew and John Whiteside (Eds.). ACM, New York, NY, USA, 235-242. DOI=http://dx.doi.org/10.1145/97243.97279

Mitchell, D. K. (2000). Mental Workload and ARL Workload Modeling Tools (ARL-TN-161). Aberdeen Proving Ground.

Mitchell, D. K. (2003). *Advanced Improved Performance Research Integration Tool (IMPRINT) Vetronics Technology Test Bed Model Development* (United States, Army Research Laboratory, Human Research & Engineering Directorate). Aberdeen Proving Ground, MD: Army Research Lab.

Nielsen, J. 1995. Usability inspection methods. In *Conference Companion on Human Factors in Computing Systems* (CHI '95), I. Katz, R. Mack, and L. Marks (Eds.). ACM, New York, NY, USA, 377-378. DOI=http://dx.doi.org/10.1145/223355.223730

Paas, F. (1992). Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach. *Journal of Educational Psychology*, 84, 429–434.

Salvi, L. (2001). Development of Improved Performance Research Integration Tool (IMPRINT) Performance Degradation Factors for the Air Warrior Program. Retrieved from papers2://publication/uuid/197638AB-1200-4BFE-A922-E5E12FB25BD6

Spradley, J. P. (1979). *The ethnographic interview*. Belmont, CA: Wadsworth.

Swain, A.D. (1964) THERP *(Report SC-R-64-1338)* Sandia Corp.: Albuquerque, NM.

Taylor, R. M. Situational Awareness Rating Technique (SART): The Development of a Tool for Aircrew Systems Design. *Proceedings of the NATO Advisory Group on Aerospace Research and Development (AGARD) Symposium on Situational Awareness in Aerospace Operations;* AGARD-CP-478, 3/1-3/17; NATO – AGARD: Neuilly Sur Seine, France, 1989.

Wiedenbeck, S. 1985. Novice/expert differences in programming skills. *Int. J. Man-Mach. Stud.* 23, 4 (October 1985), 383-390. DOI=http://dx.doi.org/10.1016/S0020-7373(85)80041-9

Yerkes, R., Dodson, J. (1908) The Relation of Strength of Stimulus to Rapidity of Habit-Formation Journal of Comparative Neurology and Psychology. 18: 459–482.

APPENDIX A: QUESTIONNAIRES

NASA Task Load Index (TLX)

PARTICIPANT INFORMATION
Participant ID
Date
TASK INFORMATION
Task Name
NASA TLX SURVEY
Directions: Please indicate with an "X" on the scales provided, the level that most appropriately reflect your impressions about the graphical user interface (GUI) you used to complete your task. *N/A indicates "Not Applicable."
MENTAL DEMAND How mentally demanding was the task?
Very Low ... Very High   N/A
PHYSICAL DEMAND How physically demanding was the task?
Very Low ... Very High   N/A
TEMPORAL DEMAND How hurried or rushed was the pace of the task?
Very Low ... Very High   N/A
PERFORMANCE How successful were you in accomplishing what you were asked to do?
Perfect ... Failure   N/A
EFFORT How hard did you have to work to accomplish your level of performance?
Very Low ... Very High   N/A
FRUSTRATION How insecure, discouraged, irritated, stressed and annoyed were you during completion of the task?
Very Low ... Very High   N/A

(Adapted from Hart and Staveland's NASA Task Load Index Method.)

NASA Task Demand Comparison

PARTICIPANT INFORMATION
Participant ID
Date
TASK INFORMATION
Task Name

TASK DEMAND COMPARISONS		
Directions: For each of the following pairs, please check the box of the characteristic you felt was weighed more heavily as you performed the task.		
☐ Physical Demand	OR	☐ Mental Demand
☐ Time Demand	OR	☐ Mental Demand
☐ Performance	OR	☐ Mental Demand
☐ Frustration Level	OR	☐ Mental Demand
☐ Effort	OR	☐ Mental Demand
☐ Time Demand	OR	☐ Physical Demand
☐ Performance	OR	☐ Physical Demand
☐ Frustration Level	OR	☐ Physical Demand
☐ Effort	OR	☐ Physical Demand
☐ Time Demand	OR	☐ Performance
☐ Time Demand	OR	☐ Frustration Level
☐ Time Demand	OR	☐ Effort
☐ Performance	OR	☐ Frustration Level
☐ Performance	OR	☐ Effort
☐ Effort	OR	☐ Frustration Level

Situational Awareness Rating Technique (SART)

Instability of Situation
How changeable is the situation? Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

1 2 3 4 5 6 7

Complexity of Situation
How complicated is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

1 2 3 4 5 6 7

Variability of Situation
How many variables are changing within the situation? Are there a large number of factors varying (High) or are there very few variables changing (Low)?

1 2 3 4 5 6 7

Arousal
How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

1 2 3 4 5 6 7

Concentration of Attention
How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focussed on only one (Low)?

1 2 3 4 5 6 7

Division of Attention
How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focussed on only one (Low)?

1 2 3 4 5 6 7

Spare Mental Capacity
How much mental capacity do you have to spare in the situation? Do you have sufficient to attend to many variables (High) or nothing to spare at all (Low)?

1 2 3 4 5 6 7

Information Quantity
How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

1 2 3 4 5 6 7

Familiarity with Situation
How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1 2 3 4 5 6 7

This page intentionally left blank.

DISTRIBUTION

4 Lawrence Livermore National Laboratory
Attn: N. Dunipace (1)
P.O. Box 808, MS L-795
Livermore, CA 94551-0808

1 Troy Hartwig
14520 Botts Road
Kansas City, MO 64147

1 JD Selby
14520 Botts Road
Kansas City, MO 64147

1	MS0899	Technical Library	9536 (electronic copy)

For LDRD reports, add:

1	MS0359	D. Chavez, LDRD Office	1911

For CRADA reports add:

1	MS0115	OFA/NFE Agreements	10012

For Patent Caution reports, add:

1	MS0161	Legal Technology Transfer Center	11500

Sandia National Laboratories