The value of 3D product model deployment to complex production and assembly processes

by

Carl Joseph Kirpes

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Program of Study Committee:
Guiping Hu, Co-major Professor
Dave Sly, Co-major Professor
Stephen Gilbert
Cameron MacKenzie
Gul Okudan-Kremer

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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NOMENCLATURE

2D	Two-dimensional
3D	Three-dimensional
BOM	Bill of Materials
BOP	Bill of Process
CAD	Computer-Aided Design
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
CRM	Customer Relationship Management
ECO	Engineering Change Order
ERP	Enterprise Resource Planning
FMEA	Failure Modes and Effects Analysis
HMI	Human-Machine Interface
ISE	Industrial and Systems Engineer
NCM	Non-Conformance Management
mBOM	Manufacturing Bill of Materials
MES	Manufacturing Execution System
MCO	Manufacturing Change Order
MPM	Manufacturing Process Management
PDM	Product Data Management
PFEP	Plan For Every Part
PFMEA	Process Failure Modes and Effects Analysis
PLC	Programmable Logic Controller

PLM	Product Lifecycle Management
SLP	Systematic Layout Planning
SOP	Standard Operating Procedure
SPC	Statistical Process Control

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ABSTRACT

The 3D product model, a tool long used in the design phase, has continued to evolve to play a critical role beyond the design process. Enabled by emerging technologies, the 3D product model can now be deployed to production and assembly processes. Prior to this research, the value of the application of the 3D product model in the production and assembly process was believed to have qualitative value yet that value was unknown quantitatively. This dissertation aims to answer the question, what is the value of the 3D product model use in production and assembly processes? The authors start by outlining the evolution of the 3D product model over time, developing (16) research themes that provide the foundation for a more comprehensive 3D product model research ontology. The authors then discover (5) value areas when deploying the 3D product model in the production and assembly processes and develop quantitative models for those value areas. Using applied research, the authors deployed electronic documentation inclusive of the 3D product model to a production and assembly process—determining how accurately and quickly a production and assembly team could build the product using interactive, electronic documentation, including the 3D product model, as a means to understand design intent as opposed to printed Bills of Material (BOMs) and paper two-dimensional (2D) drawings. This research recognizes that through the deployment of interactive 3D product model electronic documentation to the production floor, organizations can take a step towards having a digital twin of the produced product and lay a foundation for further adoption of industry 4.0 practices. This dissertation provides a contribution to the body of knowledge that serves as a platform for industry and academia alike to now understand the value of deploying the 3D product model to production and assembly processes, quantify that value, and project 3D product model future applications and trends.

CHAPTER 1. GENERAL INTRODUCTION

The motivation behind this dissertation results from my desire to make the world a more effective, productive, and resilient place. As I look to make a difference, applying my natural strengths has allowed me to have greater impact. My experiences in engineering (education and industry) have supplied the context in which I can apply these natural strengths, and my technical and social abilities further strengthen my aptitude as a leader in engineering. Double degrees in Industrial Engineering and Mechanical Engineering have helped me analyze engineering problems at a component level as well as at component-interaction and systemic levels. My Masters in Systems Engineering further honed these abilities. Applying this aptitude, coupled with academic research and industry experiences, I observed reductive approaches used to address research questions. These approaches led to inapplicable solutions to original real-world problems.

These divided approaches stretch beyond engineering. As a leader, I've seen divided teams struggle to reach their organization's goals, and I've helped those teams unify and build upon each individual's strengths to then achieve team objectives.

In industry, I built upon principles derived from those leadership experiences. Working as an Applications Engineer with an industrial-engineering software company, I viewed the same divided approaches applied to situations in engineering industry. I observed manufacturing process-engineers attempting "Throw-it-over-the-wall" solutions; that is, engineers did not consider soft-systems interaction in conjunction with the hard-systems. Each engineer was optimizing one component of the system and then, metaphorically, passing it over the cubicle wall so the next engineer would optimize a separate component. This approach neglects the interaction between components, which decreases the effectiveness and impact of the resulting system.

First-hand, I have repeatedly seen manufacturing plants where engineers are divided into divisions with separate responsibilities such as engineering product design, line balancing, work instructions, and time studies. However, in reality engineering product design, line balancing, work instructions, and time requirements are all inherently integrated—as a change in any one "division" ripples affects among all others. My objective is to help companies apply systemic approaches that empower each division and merges divisions' capabilities into a unified whole. An integrated approach enables changes to be woven across all divisions, drastically increasing the natural flow of the overall system and capitalizing on each division's potential.

My leadership and engineering abilities are my springboard to transform engineering disciplines and industry to "play together" more systemically, with greater real-world context, creating solutions that provide greater results and impact.

Imagine if …agricultural and food processing equipment could be manufactured at lower costs and with less waste, providing more affordable means to feed more people.

Imagine if …electric vehicles (PHEVs), solar panels, and other emerging technologies could overcome their current cost-of-manufacturing mass-production barriers, providing greater relief, faster, to our interconnected world.

Imagine if … each engineer's typical, work-week tasks were completed more efficiently, allowing more time to advance family and community endeavors.

Applying systemic solutions to engineering (academia and industry) will help accomplish such dreams and more. Without holistic, systemic approaches, we lose opportunities for transformational change.

Globally, engineers generate remarkable solutions using current, common industry methods. However, while society and engineering has increased in complexity and integration, engineering problem-solving and technology deployment has not kept pace. The application of systemic approaches enabled by emerging technologies, suited to address increasingly complex systems, would empower engineers and leaders alike. The intent of this work is to step beyond the current mold and practice, apply, and catalyze more comprehensive, integrated, and systemic engineering-and-social solutions.

I feel a responsibility to use my engineering talents and leadership abilities to the fullest. I have undertaken the effort of developing this dissertation so I can use my internal drive, talents, and abilities to catalyze adoption of systemic-integrated “woven-design” engineering. I have seen how neglect of interactions between components in a system, and neglect of interactions between the systems themselves (i.e., with natural and man-made “ecosystems”), reduces the effectiveness and impact of many engineers and aspiring leaders. We must upgrade engineering disciplines to an integrated-systemic approach.

In short, I am impelled to create and implement effective, systemic engineering, so others can use these woven-design, systemic approaches as a springboard to enhance global productivity, resilience, and well-being. In pursuit of the fulfillment of this vision, this dissertation focuses on the value of deploying 3D product models to complex production and assembly processes.

The research to date has concluded that the 3D product model has value beyond product design [1, 2]. The body of literature discusses how the 3D product model improves the efficiency and reliability of assembly process design, reduces process planning problems, and shortens process planning cycles. However, the current body of knowledge does not provide any data or methods that support these findings, and thus the research is not repeatable. The research in this dissertation is differentiated in that it provides a methodology to determine the value of the 3D product model deployment to complex production and assembly processes so that the research can be repeated by others. Research publications also highlight why bringing the 3D product model to the assembly process is a concept that did not emerge until into the 2000's and 2010's, as before that time the application of the 3D product model to the assembly process was limited by software capability and availability [3,4]. The emergence of the enabling technology provides the means for the application of the 3D product model to the production and assembly process and the means through which to study the value of doing so. In addition to the fact that software has now made the deployment of the 3D product model to the production and assembly process feasible, there are also other enabling factors that are coming to fruition which are removing limitations [5]. Examples include software that can transform the engineering bill of materials (eBOM) to the manufacturing bill of materials (mBOM) [5], the development of Manufacturing Process Management (MPM) software [9], technology that can extract 3D product model data [10-15], and the growth of virtual manufacturing knowledge [16,17]. The removal of what were previously limiting factors highlight the increased feasibility of the deployment of the 3D product model in complex production and assembly processes.

With the removal of these limiting factors comes the application of the 3D product model in ways such as integrating the 3D product model with the assembly line balancing process via process consumption [18]. This provides further basis on how the eBOM and mBOM work together, with the 3D product model tied in to manufacturing engineering applications and starts to show the value in doing so. This research is foundational to this dissertation as it demonstrates that value can be gained when deploying the 3D product model beyond the production and assembly process.

Other relevant literature includes demonstrated value in deploying the 3D product model beyond design to production and assembly. However, the research demonstrates the value qualitatively versus quantitatively. Such research includes the application of the 3D product model in the link between the Bill of Process (BOP) and the Bill of Materials (BOM) [19,20]; checking a product's configuration for assemblability using the 3D product model [21]; and enhancing shop floor work instructions to improve process planning and increase the efficiency of assembly work [22, 23].

Research to date on the use of 3D product models in production and assembly processes can be shown graphically to demonstrate the gap in the body of knowledge. Currently, a large number of published research papers have research focus on assembly, and a large number of published research papers have a focus on 3D product models, however a limited number of peer-reviewed published research papers discuss the interaction of the 3D product model and assembly processes. Even fewer document the value of deploying the 3D product model to the production and assembly process. The graphic demonstrating this gap in the body of knowledge is shown in Figure 1. This dissertation intends to fill that gap in the research.

This gap in the body of knowledge ultimately led the researcher team to the research question, what is the value of the 3D product model use in complex production and assembly processes? To begin to answer this question, the research team evaluated the deployment of other technology and process implementations to manufacturing as a basis for what similar metrics and approaches might be taken when evaluating the value of 3D product model deployment to production and assembly processes.

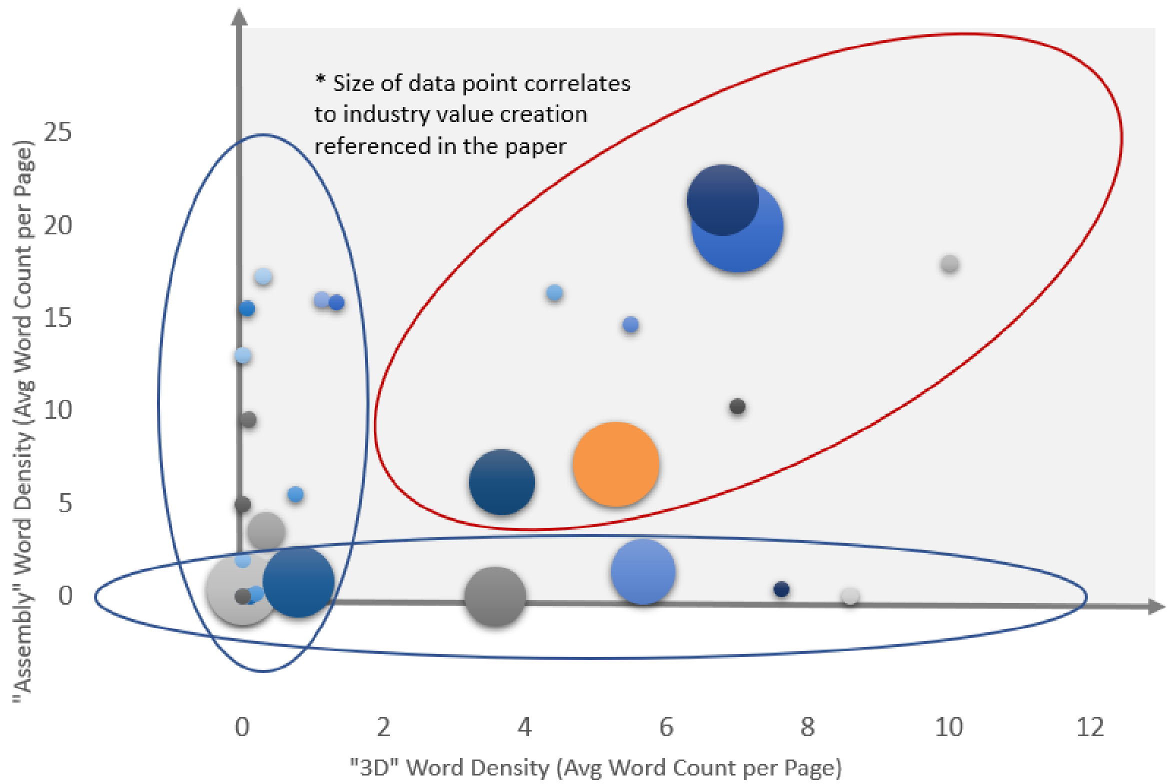

Figure 1. Gap in current body of knowledge of peer reviewed published research papers on the value of deploying the 3D product model to the production and assembly processes [1, 35]

While the body of knowledge did not present a framework for quantitatively determining the value of the 3D product model in the production and assembly processes, the authors believed that other technology deployment to manufacturing processes and the models used to determine the quantitative values of those deployments could be used to guide this research. The authors reviewed research on the deployment of Enterprise Resource Planning (ERP) systems and found corresponding studies. One such study reviewed the effect of the adoption of the enterprise systems on a firm's long-term financial success [36]. This research used measures such as Return on Investment (ROI) and Cost of Goods Sold (COGs). However, this research measured the performance of the firm at the highest level of the firm from which many areas outside of the ERP implementation could have impacted the metrics. That said, the authors did find the method of comparing the results of key metrics before and after implementation of the technology deployment to be a good framework to use in the research for this dissertation. Another research paper on ERP implementation focused on the success of the deployment of the ERP process to determine if the ERP itself was successful [37]. Metrics in the study included project on-time delivery, project on-budget, and the number of modifications to the ERP system project plan. The research then correlated these metrics to the company executive's perception of the ERP implementation success. While the authors of this dissertation do believe that the implementation of an emerging technology has merit in determining the overall success, the authors did not want to take the stance that the success of the technology was only correlated to the success of the implementation. Thus, the authors plan to track the success of the implementation while also building in other metrics that will track the success of the 3D product model deployment beyond the implementation phase.

While ERP implementation studies provided some framework for this research, the authors also looked to the deployment of new processes to production and assembly processes in the event metrics used to determine the effectiveness of those process implementations could be used in this research. One paper on measuring operational excellence focused on operational excellence profitability measures [38]. The authors of this dissertation liked the concept of tying the success of the process or technology after implementation back to profitability and thus have adopted that approach in this research.

After reviewing the adjacent research and understanding key measurable approaches that could be used to determine the value of the 3D product model in the assembly and production processes, the authors set off to answer the research question. Figure 2 highlights the approach taken by the authors to begin to answer this research question, starting at the outermost ring and working inwards, with each published research paper building on the other and getting closer to fully answering the research question.

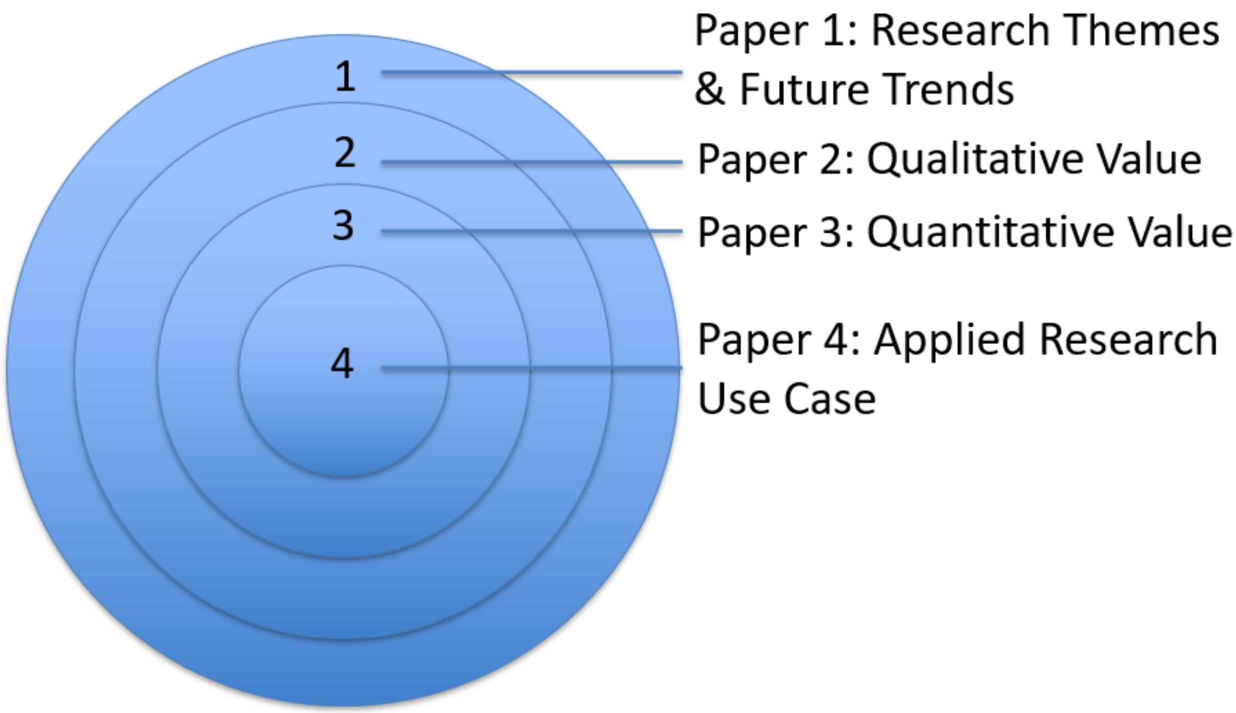

Figure 2. Approach to Answering the Research Question of the Value of 3D Product Model Deployment in Production and Assembly Processes

The second chapter of this dissertation highlights how emerging technologies set the foundation for the feasibility and applicability of deploying the 3D product model to the production and assembly process. The authors' research then evolved from there.

The third chapter of this dissertation focuses on the research evolution and future trends of the 3D product model. In conducting a systematic literature review, the authors recognized that no literature had been developed that categorized the body of knowledge into research themes and demonstrated how those research themes evolved over time. The authors developed 16 research themes as the foundation for a more comprehensive 3D product model research ontology. In addition, the authors collaborated with industry experts on the likely future trends of

3D product model applications and research, providing guidance for future work for industry and academia alike.

The fourth chapter of this dissertation explores the value of deploying the 3D product model to the production and assembly processes. The researchers' aim was to fill a gap in the body of knowledge on the value that the 3D product model has when applied to production and assembly processes. The researchers were able to determine five qualitative value areas in which the 3D product model created value in production and assembly operations.

The known 3D product model value areas from the qualitative research then led to the research question of what the quantitative value was in those areas, which set the foundation for chapter five. In this research, the authors develop a quantitative model for the value of the 3D product model when deployed to the production and assembly processes and worked with industry experts across six companies to calibrate the model accordingly. The results show which value categories generate the most quantitative value and provide guidance on where industry and academia are most likely to see the greatest impact in future applications and research.

The quantitative value model sets the foundation for chapter six, which answers the question, does electronic documentation inclusive of the 3D product model add to the production workers' ability to complete the production task? To answer this question, the research team tested how accurately and quickly a production and assembly team could build the product using interactive, electronic documentation, including the 3D product model, as a means to understand design intent as opposed to printed Bills of Material (BOMs) and paper two-dimensional (2D) drawings. The research found statistically significant improvements in production throughput time, reductions in direct labor hours per unit, and retained quality levels when deploying electronic documentation, including the 3D product model, to the production and assembly processes.

The dissertation concludes with a discussion on how through the deployment of interactive 3D product model electronic documentation to the production floor, organizations can take a step towards having a digital twin of the produced product and lay a foundation for further adoption of industry 4.0 practices. The research in this dissertation was conducted so the methodology is repeatable, ensuring other companies and researchers can benefit from the findings and application of this research.

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CHAPTER 2. BUILDING AND MANAGING THE BILL OF PROCESS TO STREAMLINE THE ENTERPRISE – AN EMERGING TECHNOLOGY ENABLED SYSTEMS APPROACH

Dave Sly and Carl Kirpes

Industrial and Manufacturing Systems Engineering (IMSE), Iowa State University

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Abstract

In both academia and industry, industrial engineering has long been departmentalized. Students take classes focused on specific topics such as human factors, time studies, line balancing, or linear programming. Professors specialize in a specific niche to become experts on a topic. Practitioners' industrial engineering responsibilities become divided between individuals, with organization or departmental silos generating communication and information sharing barriers. While each of these individual experts are important, a systemic approach that combines the potential each of these experts offer into transformational results is being enabled by cloud-based industrial and systems engineering technology. This chapter will focus on how emerging, holistic cloud-based approaches are creating a more systemic application of industrial and systems engineering across companies, universities, and value chains. The authors also believe that this technology will further allow for academic and industry collaboration on the integration of all of the industrial and systems engineering practices across disciplines.

Keywords

Assembly; process planning systems; concurrent engineering; automotive industry applications; manufacturing industry applications

The New Age Industrial Engineer—Value in the 21st Century

Is industrial and systems engineering truly valuable? Do industrial and systems engineers (ISEs) create value for their organizations? Since the days of Frederick Taylor, ISEs have worked in organizations performing time studies, generating line balances, writing work instructions, completing ergonomics assessments, ensuring quality, and completing Process Failure Modes Effects Analysis (PFMEA). However, as organizations have grown more complex, often different ISEs are performing varying degrees of each of these functions for their company, and in academia, different ISEs are doing research and teaching specific segments of these topics. This siloed approach allows for deep knowledge and strength within a discipline but ignores the opportunity for collaboration between them. Worse yet, ISEs will recollect the data on a process step (time study, ergo, work instructions, etc.) each time that data is needed for a specific function as opposed to referencing and maintaining a common process database. If we are not saving, sharing, and maintaining process data is that because it is not inherently valuable? And if the data does not have value, what does that say about our profession that recollects that data time and time again? As the founders of efficiency, how has the process of performing industrial and systems engineering become so inefficient?

While this view may seem degrading at first, when looked at through another lens, such a view is exhilarating because of the potential that exists in improving the way we, as ISEs, practice our profession. ISEs have contributed greatly to the efficient operation of our factories and businesses, and now is the time to direct these skills inwardly and become the imaginary engineers that IEs are often called by other engineering professions. Imagine if ISEs had efficient and effective ways to implement their industrial and systems engineering skills sets, across multiple industrial and systems engineering disciplines, leveraging the same process step database across the organization. Imagine if the ISEs took the same approach to building and managing the Bill of Process (BOP) as the mechanical and electrical engineers take with the Bill of Materials (BOM). Such a change is possible, and we are on the cusp of that emerging frontier when taking an enterprise-wide, technology-enabled BOP approach.

Creating, Managing, Maintaining the BOP Effectively

The BOP is more than just a Process Routing. As stated by Littlefield in *The Evolution of MOM and PLM: Enterprise Bill of Process*, the BOP encompasses everything known about how to manufacture the product represented by the BOMs. It includes the plants (layout), resources (machines and tooling), work instructions, ergonomics assessments, quality plans, and process configuration rules [1]. Like a BOM, a BOP needs to be constructed, managed, and maintained. This effort takes collaboration which requires some common definitions.

The fundamental component of a process is the activity (often called a task) which represents the smallest amount of movable work. This definition is important because it represents the fact that Activities can be relocated to different people or machines. As shown in Figure 1, this relocation requires reaggregation at the new location, which is often performed automatically.

Attaching attributes of time, tooling, ergonomics, quality, and part consumption to an activity ensures that this information is available for aggregation, reconciliation, and reporting in the future. For example, if you drag and drop five Activities to an assembly line workstation, you now can aggregate (compile) the total time for the operator, the total ergonomic risk, the quality control plans, and even the shop floor work instructions. Often these engineering functions are those which take an engineering department the most time, require the least skill, and generate the greatest error.

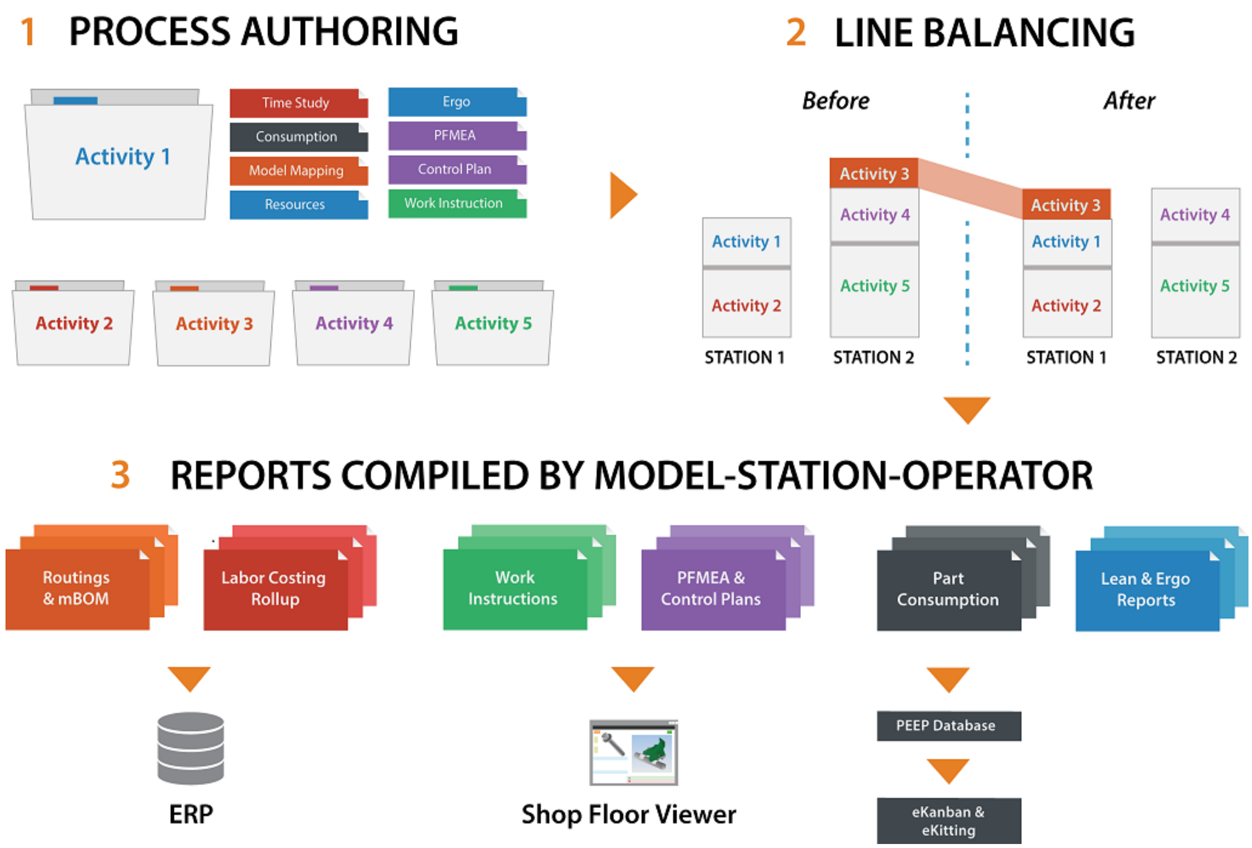

Figure 1. Activity assignment and compilation in the BOP.

Of course, this means that all members of the Process Engineering team are collaborating around these common definitions of work and that new definitions of work (Activities) are only created when a unique task needs to be performed, otherwise existing Activities should be reused. This is identical to the benefit of reusing existing parts in a new BOM instead of creating new fasteners and brackets for every new product. Reusing Activities across the facility greatly reduces the redundant process engineering effort and enhances the quality of the data in the system and the documentation and decisions which come from it. In fact, without Activity reuse, a BOP is cost-prohibitive to create and maintain.

In order to reduce Activity proliferation, it is critical to Model and Option code the activities so that they can be referenced into the Process Routings created from the BOP. Figure 2 shows an example of Model Option code applied to Activities. This simple concept borrowed from BOM management means that we can have a master BOP for a department or assembly line which contains all relevant Activities which are currently performed. Since each Activity knows what Models and Options it is appropriate for, the Process Engineer can automatically filter the master BOP into an order-specific Process Routing, and generate reports and documentation for time, tooling, instructions, and quality on demand. Another feature is the ability to use “Where Used” queries on Activities to understand what all Routings (Model and Option families) this process task is associated with. Therefore, just like the need to understand what products are affected by this BOM component change, we can understand what all products are affected by this process or tooling change.

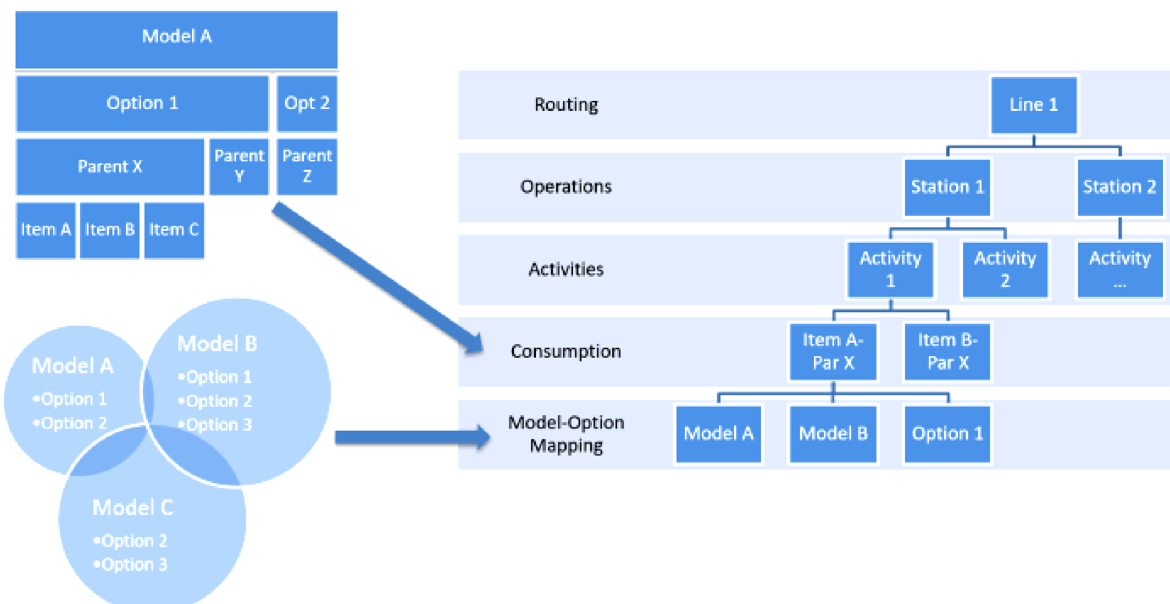

Figure 2. Model and option mapping to make activities reusable in many routings.

Most importantly, a common definition around Activities allows the ergonomist to reference the times and task descriptions from the time study people or the standard operating procedure (SOP)/work instruction authoring person to reference the time, tooling, and part consumption attributes entered by other engineers. Collectively, this process information will be more accurate, more complete, and of much greater value to the organization than the set of disconnected, incomplete, and out-of-date spreadsheets which Industrial Engineers commonly adhere to today. With a complete and accurate BOP, organizations can make quicker and more accurate decisions on launching new products and processes, adjusting production volumes, or justifying and implementing process improvements. In short, companies will bring new products to market sooner, with less cost, and better quality.

Visualizing the Product and the Process in a Collaborative Way

Video and 3D product models are two relatively new technologies which enhance the quality of the process steps being defined and documented. Most importantly, both technologies greatly enhance the BOP usage and value throughout the organization and, thus, the perceived value of the ISE community responsible for creating and maintaining them.

Videos of the Process

To truly maximize the value ISEs can bring to their organizations through the Activities mapped to the BOP, every organization must have a video associated with every process Activity maintained. That is a strong statement and is often in conflict with rules in the organization prohibiting video, but those rules MUST change. Yes, this technology is just that important. If a picture is worth 1,000 words, then a video is worth millions.

Videos can be used to create or verify observed time studies or benchmark predetermined ones, they show the workplace layout, the tooling used, the operator movements necessary for work instructions or ergonomic studies, the material handling equipment, the lighting, the noise and interactions with other operators and machines, and so much more. Collectively, the video IS the visualization of the BOP this chapter seeks to define.

Creating videos is easy but using them and managing them effectively takes help from technology. Most importantly, videos can capture many activities, and they can do so over multiple operator cycle times which may comprise of many Activities each. Figure 3 shows how one video can be comprised of many activities.

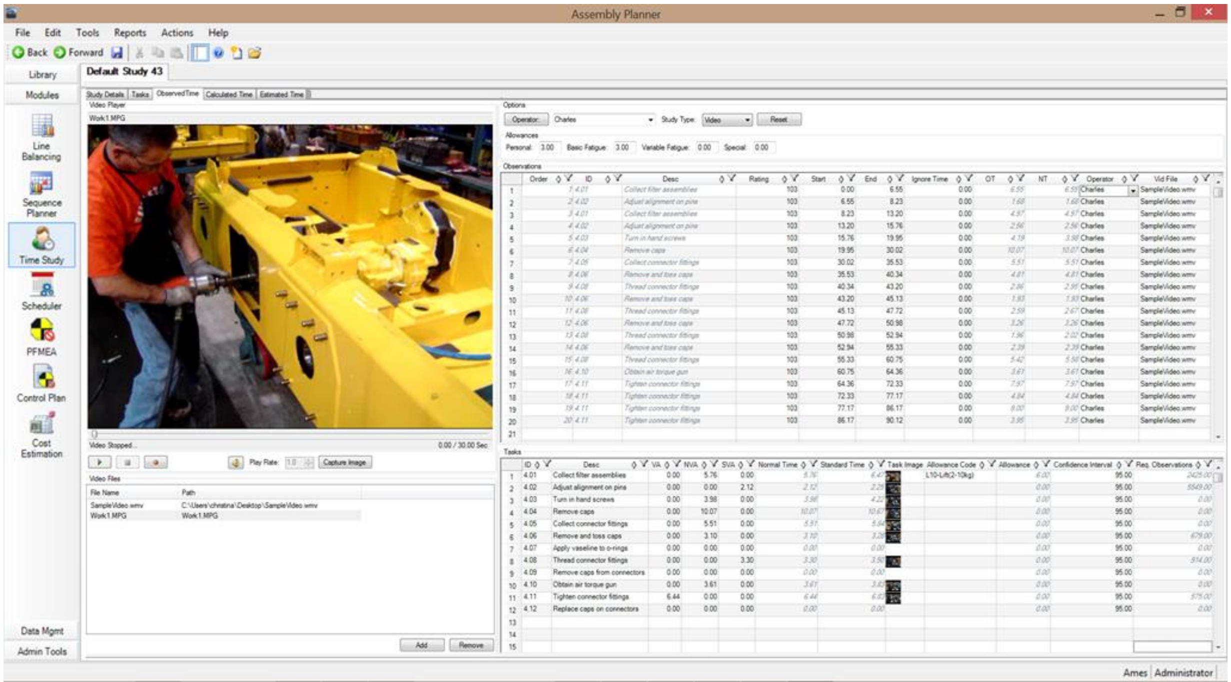

Figure 3. Observed multi-cycle activity time studies from a video.

The video recording needs to be easily segmented and cataloged by the engineer. This can be done by breaking the video into individual files or more appropriately associating file and time stamp links from a video file to Activities. In either case, each Activity should map to at least one video recording segment and perhaps several segments which might represent multiple observations (observed time study). The default video linked to each Activity will be the one referenced for work instructions, ergonomic studies, and predetermined time studies. Any employee in the company should be able to quickly hyperlink to this video from the system where they view their activity list. Common locations include process routings, shop floor manufacturing execution systems (MES), and enterprise resource planning (ERP) systems. A hyperlinked video is a considerably more effective way to train and inform workers than traditional printed SOP documents with photos.

Finally, once Activities have been reassigned to operators in the factory, the line balancing, software can recompile these Activity videos in sequence to create a video of the new operator operation.

3D Models Linked to the Process

Once you have established a link between the BOP and the BOM by having your process Activities consume your BOM components, you can leverage your 3D product models in amazing ways. A key enabler of this emerging trend is that 3D product model viewers are becoming very common in manufacturing organizations today. This is because most of the components manufactured and assembled today have a 3D model associated to them and the software and hardware cost of 3D viewing technology has come down substantially.

The most basic use of this 3D integration is the ability to view components in the BOM when you are consuming them by the process. Often this means simply selecting a hyperlink on a component to view that component; however, more advanced systems allow you to select components from a 3D assembly and drag and drop them to the process Activity that is consuming them. Then you can view a consumption-color-coded 3D assembly and see which components are consumed and which are not.

Having a 3D component or assembly linked to a process Activity then makes creating and annotating work instruction documents considerably easier and accurate and is particularly helpful for new products where photos may not be available. In this situation, it can also be helpful if your system allows you to associate a 3D model link to each Model/Option-dependent component that your activity is consuming. Put another way, if your Activity assembles three different alternators, then you may wish to associate the three different alternator models to the Activity so that the proper model image shows up when the Activity is referenced in a Routing or work instruction for a specific Model/Option combination.

Finally, for assembly-driven organizations, 3D Models can be very helpful when creating and visualizing assembly precedence diagrams and Yamazumi charts. Figure 4 shows a 3D process model that aligns with the associated Activities in the Yamazumi chart, and Figure 5 shows a 3D model that correlates to the associated precedence chart. When editing product assembly precedence in the chart view, you can see the product automatically assemble itself. Simply selecting the Activity from the precedence map causes only the components assembled up to that Activity to display and will show the components in the selected Activity in a different color. With this approach, the assembly precedence can be visually validated.

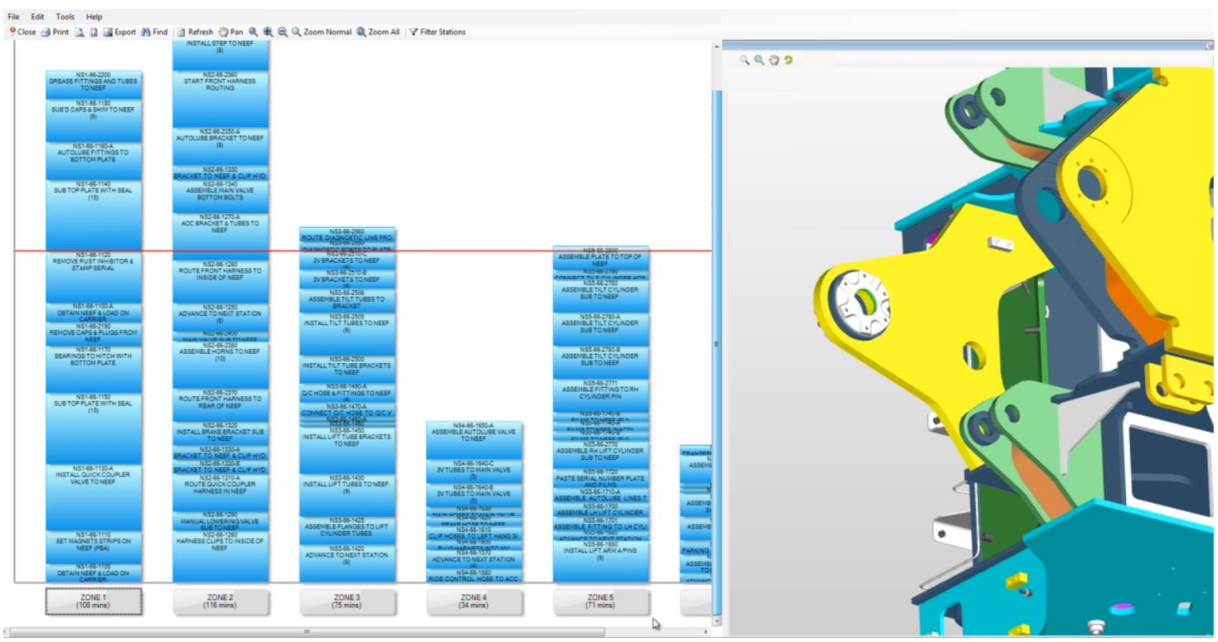

Figure 4. 3D product model linked to a Yamazumi line balance chart.

Linked Yamazumi charts work in much the same way. Engineers can select a tile in the chart which is associated with an Activity and see the visual image of the assembly as of that specific Activity. Moving Activities around between stations (drag and drop the tiles) will then change the view of the product at each station. Engineers can then snapshot these product assembly views from the Yamazumi editor to create images for Activity-based work instructions or record the Yamazumi query (tile by tile) and generate a short video of a 3D virtual assembly for that operator. This emerging trend adds a lot more organizational value to creating and using Yamazumi charts.

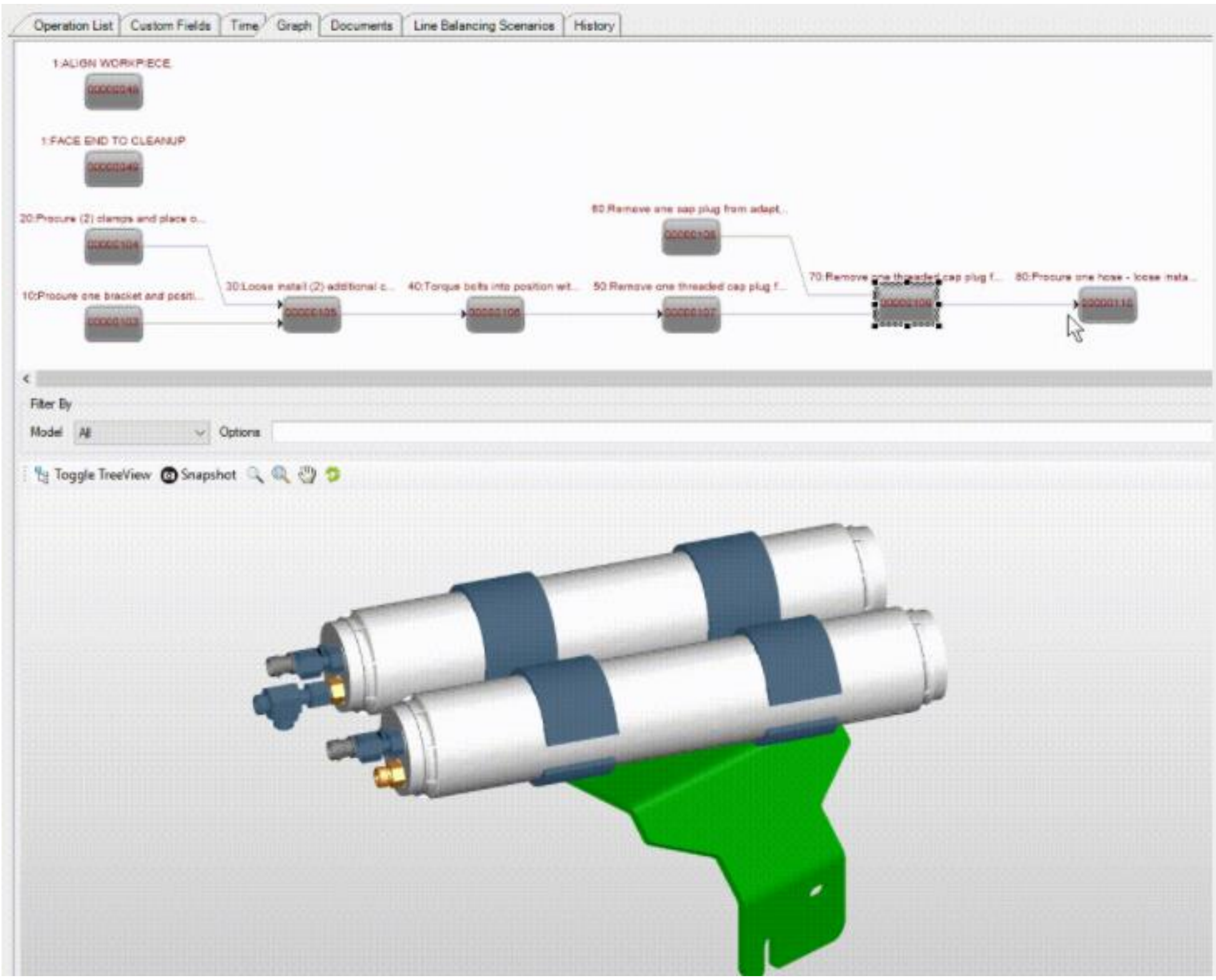

Figure 5. Assembly precedence diagram linked with 3D product model.

Effectivity, Revision, and History Control in the BOP

In any managed collaborative environment, it is critical to have rules and controls to provide data integrity and user accountability. Just like with the BOM management technologies which have extended from simple spreadsheets through to product data management (PDM) and product life cycle management (PLM) environments, BOP databases need similar tools.

Now that we are managing, maintaining, and collaborating around Activities in the same way we do with components of the BOM, revision and effectivity can be applied.

Revision Control

Revision control is often a labeling technique to quickly understand that a change to this shared Activity has occurred. Often this can be coordinated with multiuser check-in and check-out mechanisms to ensure that multiple users are able to edit or view within the same BOP without corrupting the data between themselves. Additionally, workflow systems can be incorporated to ensure that revisions are reviewed and/or approved prior to release.

Effectivity Dates

Effectivity date range coding of the Activities works very similar to how routings and components can be effectivity date managed within ERP systems. The engineer simply defines a date (or event, or product series) where the company should transition from using the old Activity to the new one. Effectivity dates enable a common process plan BOP to be used in an environment where Activities referenced by the BOP are changing daily.

History Tracking

Finally, history tracking is the police of collaboration. It ensures that actions made by users of the BOP system are tracked and searchable so that should problems arise, accountability can be made, training enhanced, and mistakes reduced or at least quickly corrected.

Mapping the BOP and BOM and Reconciling the Process to the Product

Perhaps the most valuable benefit of a BOP which contains reused Activities is the ability for those Activities to consume (map to) the components (or machined features) in the BOM for which they are responsible. For example, a task to assemble an alternator onto a car may involve the alternator, a bracket, and perhaps a few bolts and washers. If the Process Engineer defines the Activity as consuming those parts from the BOM, then it is now possible to ensure (reconcile) that all Activities in the BOP consume all components in the BOM—no more and no less. This is critically important when large and complicated assemblies are launched to the production floor and the engineer finds out that the work instructions do not match the product they are producing and the parts in each station do not match what the operator needs.

Performing this consumption mapping process requires a lot of manual effort or some very intelligent software and a well-defined collaboration process.

1. First, your Activities must use the same Model and Option configuration rules as your BOM and your BOP, and the BOM must be defined for the same area of production (i.e., Assembly line 6). This way you can be certain that the components assembled in that area are assembled with the processes in that area.
2. Second, your Activities must be able to consume part numbers by Model and Option code. For example, if you have an Activity that assembles an alternator on a car, then this Activity could apply to four different alternators, depending on which of the four option codes mapped to that Activity are being referenced. Therefore, the engineer needs to specify all four alternators as consumed by the Activity and map the correct Option code to each of those mutually exclusive consumption events. Luckily, there is software available which can read a configured BOM and automatically populate the part consumption to configured Activities in the BOP. (Pretty cool huh?)
3. Third, we need to reconcile the consumption of components by an Activity to the BOMs for which that Activity consumes components. All BOMs in the master BOM mapped to all Routings in the BOP.
4. Finally, we can address errors arising from a failed BOM–BOP reconciliation until we achieve a resolution good enough to be launched on the production floor.

Industrial and Systems Engineering Technology Enablement—PLM–ERP–MES

For ISEs to bring systemic change to the way they perform industrial and systems engineering as described in the sections above, the means to do so must exist. Just as the automobile becoming a more efficient and effective means of transportation could not exist before the invention of the wheel and the internal combustion engine, the means for ISEs to manage data at the smallest process step and then share that data across multiple engineering tasks cannot be done without the use of PLM and MES. Today, many organizations try to utilize ERP as the means to process all their data and thus have all data go into and flow from the ERP system. However, ERP systems are great at showing transactions that have happened (i.e., an accounting function) and for making future predictions about what parts and materials are going to be required (i.e., a purchasing function) but are not the right tool for the design or execution functions in an organization.

ERP systems are designed to integrate the information between manufacturing, inventory management, sales, accounting, service, and the customer relationship management (CRM) software. The key objective of ERP is to provide a high level of integration necessary to efficiently synchronize these functions so that the organization can make effective high-level decisions more responsively. In particular, the synchronization of sales to manufacturing, inventory, and accounting can have a profound impact on ensuring that the organization is delivering the “right” products to the “right” customers at the “right” time.

In this capacity, ERP systems are planning applications that are responsible for ensuring that parts, people, and tooling are available to produce what customers want to purchase, and the ERP system’s primary “customer” is upper management who needs access to this information in a quick and coordinated manner.

PLM systems are essentially engineering design and which provide the manufacturing “Plans” for the ERP to execute (i.e., the design function), whereby MES applications are shop floor execution applications which functionally implement the manufacturing “Plans” dictated by the ERP system’s “Build Schedule” (i.e., the execute function).

ERP systems are not the right environment for execution, and ISEs need the tools to operate in an execution-based environment. Figure 6 shows the data flow between these various tools that enable ISEs to complete their roles and responsibilities on a platform that enables efficiency and effectiveness.

To better understand this graphic and the way in which ISEs can apply industrial and systems engineering principles to the practice of industrial and systems engineering itself, understanding the foundation for the way in which these platforms interact is important.

As seen in the PLM, MES, and ERP data flow diagram (Figure 6), the majority of data required between PLM and MES applications are detailed “execution-oriented” and of no value to the ERP system. As such, attempting to integrate all of this information within ERP creates a great deal of complexity and cost without any benefit. In fact, the significant amount of data that would need to be imported into and out of ERP and associated to ERP objects would result in an unnecessary overall system performance reduction to all users. In particular, the Routing and Tooling information required for PLM and MES is substantially more detailed than what is required by the ERP. Most ERP implementations define a routing in terms of Operations that require a composite time, whereby in PLM systems, Operations are defined from Activities which are defined by Worksteps that often are comprised by Elements.

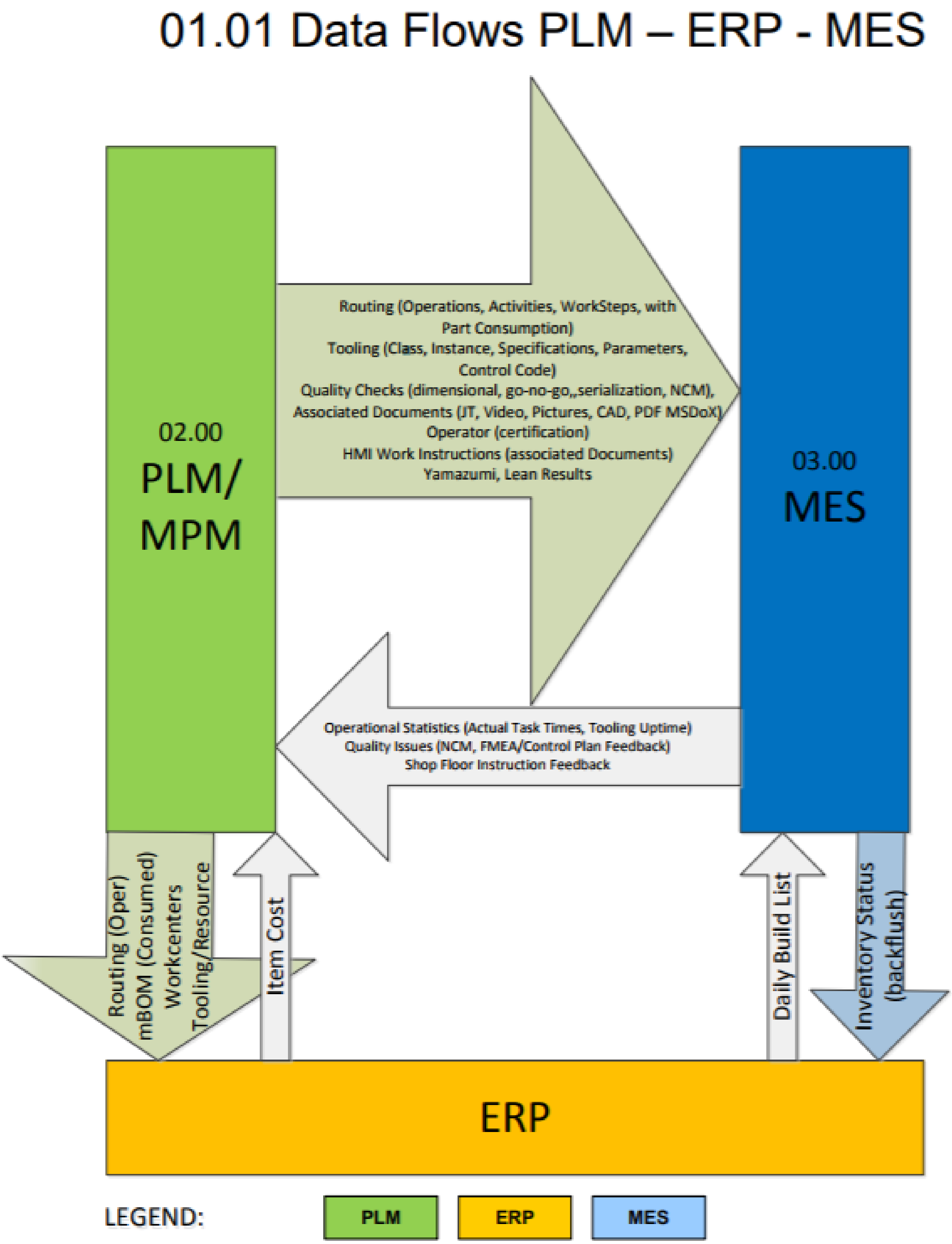

Figure 6. Data flows—PLM–MES–ERP.

Each of these process detail levels may contain from 2 to 100 records, and therefore, a simple 1 Operation record in ERP could represent from at least 10, to several hundred thousand records in PLM. This similar analogy applies to MES, whereby Activities and Worksteps form the backbone of a process description to an operator and elemental data is defined in machine code numerical control (NC), programmable logic controls (PLC), etc. to the tooling. Of course, PLM and MES systems handle this complexity via configuration rules so that this process detail needs to only be defined once but referenced in hundreds or thousands of different Routings. These configured process details at the Activity and Workstep levels also require sophisticated engineering change procedures, involving version, platform, or serialized effectivity, in a manner far more detailed than what ERP systems typically manage, and their users are experienced with.

As such, managing this data, detail, and complexity among a focused group of engineers in the PLM and MES applications, and their associated integration, will result in a more organizationally effective approach than would be gained by Routing this workflow through ERP.

Within the PLM—Manufacturing Process Management

Within the PLM lives the manufacturing process management (MPM) system. The objective of MPM is to define the process, manage multiple versions of it (i.e., prior versions, active versions, and future planned alternates), and export the “Active” process with Effectivity attributes (i.e., serialized, version, or platform) to MES and PLM systems for Execution. Figure 7 shows the data flow within an MPM system.

The typical workflow for a new assembly or the more typical engineering change to an existing assembly looks as follows:

1. Engineering change order (ECO)/manufacturing change order (MCO): Receive ECO and create MCO and define change Effectivity.
2. Manufacturing BOMs (mBOM): Author or edit an associated mBOM.
3. mBOM Downstream Data: Electronically identify the associated downstream manufacturing data affected by the mBOM changes. Best accomplished via associative data linkages.
4. Process Engineering: Author or edit all associated routings and process objects (i.e., operations, activities, elements—includes time estimation).
5. Tooling: Evaluate tooling requirements (i.e., jigs, fixtures, automation code development [NC/coordinate-measuring machine (CMM)/Robotic/Lightboard/PLC]).
6. Work Instructions: Define work instruction notes and associated documents and images.
7. Line Balancing: Evaluate work assignment to stations and operators (i.e., may involve line balancing/man–machine analysis). This subsequently results in the assignment of parts and tools to those stations.
8. Transactional Requirements: Define transactional requirements (inventory backflush, inventory/PFEP triggering, safety equip specification, quality [FMEA/Control Plan/Statistical Process Control (SPC)/Nonconformances (NCM)], genealogy, tooling details).
9. Publish mBOM and routing to ERP.
10. Publish instructions (with associated process, part, tooling data) to MES.
11. Publish part consumption changes to PFEP.

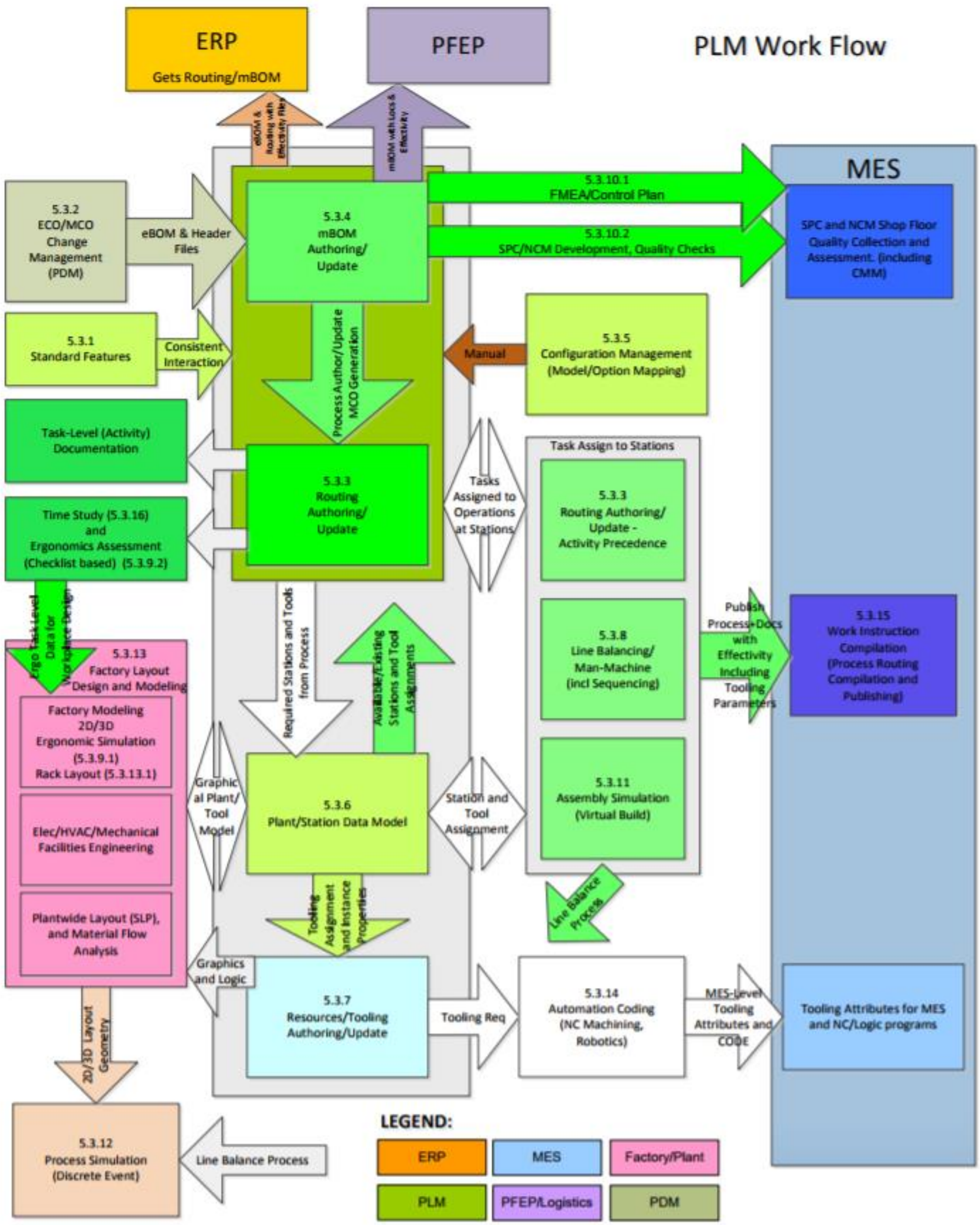

Figure 7. MPM workflow.

By utilizing an MPM system and the process outlined previously, changes to the design which are triggered by an ECO update the engineering BOMs which can then be compared against the existing mBOMs and an associated MCO can be issued to change the materials needed in the manufacturing process to accommodate the engineering change. Within the MPM system, when the mBOM changes, the associated activities being performed in the manufacturing/assembly operation are flagged to be updated accordingly, which then triggers updating the required tools, work instructions, line balance, etc. Rather than in a traditional model where each of these operations has their own data set which must be updated independently (often by different individuals), in the MPM framework the change is cascaded through the MPM system. This mitigates the room for error in which one part of the engineering subset is updated with the correct information, let’s say the work instructions, but another area is missed, let’s say the tooling requirements are not updated accordingly, leading to (in this example) a set of work instructions that the operator does not have the correct tools to perform. When errors such as this are mitigated, it allows for significant improvements in being able to implement engineering changes into production. With best-in-class MPM and MES systems, before a change is ever implemented, the data model for the change can be reconciled (similar to how accounting can reconcile the books) to ensure the product, process, plant, and resources are all updated and accurate for the change to effectively take place.

Case Studies

While many organizations are still using separate excel spreadsheets or making expensive modifications to their ERP systems to force that system to perform execution functions that the ERP was not designed to do, others are on the emerging frontier and have started to implement best-in-class PLM and MES systems, some out of necessity and others by choice.

One such example was at a large appliance manufacturer, who lost one-third of its workforce in 1 day due to legislative changes. The plant was set to run at a given line rate, and without one-third of the workforce, the plant would be forced to shut down unless the line rate could be adjusted accordingly. Adjusting the line rate requires rebalancing the line and updating work instructions, ensuring parts are sent to the correct stations with the rebalance, moving tooling accordingly, etc. Under traditional operating practices, such changes would not have been feasible in a short period of time given the vast magnitude of tasks and activities that engineers would need to update to adjust the line rate accordingly. However, this organization had previously moved their data to a best-in-class MPM and MES system, where the activities were associated to operations and routings, and thus, relatively few data changes were required in order to adjust the line rate and subsequently update all associated tooling requirements, work instructions, ergonomic assessments, etc. Given this, the plant was able to adjust the line rate and continue to production with the decreased workforce. In the words of the plant manager, being able to quickly adjust the line rate with the best-in-class MPM and MES system saved the plant.

In another example, a large agricultural/industrial equipment manufacturer typically took 2 months from the release of a new product to the shop floor to where the shop floor was producing at the production target. Often the reason it took this long to reach the production target were errors found after the initial launch where information had not been updated correctly so the new product launched with missing information (e.g., an inaccurate work instruction, tooling in the wrong location, process times that were different in the line balance model than in the time study). The organization moved to using the best-in-class PLM system but had plans to continue to use traditional printed work instructions and not deploy the MES system initially yet ordered tablets to be able to utilize electronic shop floor work instructions through the MES system in the future. On the day of the product launch to the manufacturing floor, the production team discovered that the printed work instructions printer correlation settings had been set incorrectly, and the printed work instructions were useless as a result. The lead time to reprint all the work instructions was greater than a week. So, the team flipped on the MES and deployed the tablets to the floor in 1 day, thus delivering the correct work instructions to the correct stations. As a result of the work instructions being electronic, with a mechanism for the operators to provide feedback on incorrect work instruction information through the tablets, shop floor workers were able to flag any errors or changes in the work instructions back to the engineering team in the first days of production, and by the end of the week, all of the work instruction content was correct. Having the work instruction information be correct within the first week as a result of the operator feedback led to the company hitting their production target the fifth day after product launch, which had typically been a 2-month process, and the production manager was thrilled as such a quick deployment resulted in $2,000,000 of savings to the organization.

Imagining and Creating the Emerging Frontier

These examples show the power of taking the best practices of industrial and systems engineering and realizing not only the individual value of each subset of industrial and systems engineering, but the synergy when information can be shared across industrial and systems engineering disciplines through an enterprise-wide, technology-enabled BOP approach. When an Activity can be updated, and those updates apply across all associated BOPs and reconcile to the BOMs, the effort required to perform industrial and systems engineering functions is drastically reduced while at the same time increasing the accuracy of the results. Such an approach lives up to the true intent of the efficiency and effectiveness of industrial and systems engineering. As more academic institutions teach the value of how the different subsets of industrial and systems engineering work together, and as more organizations adopt best-in-class PLM and MES systems that allow them to fully realize the benefits of a cross functional industrial and systems engineering approach, the emerging frontier presented here will have transformational impact on society and the industrial and systems engineering profession. ISEs will be imaginary engineers not in the derogatory sense but in the sense that we imagined the future, and we created it.

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CHAPTER 3. THE 3D PRODUCT MODEL RESEARCH EVOLUTION AND FUTURE TRENDS: A SYSTEMATIC LITERATURE REVIEW

Carl Kirpes[1], Guiping Hu [2], and Dave Sly[1]

[1] Industrial and Manufacturing Systems Engineering (IMSE), Iowa State University

[2] Department of Sustainability, Rochester Institute of Technology

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Abstract

The 3D product model has long been a tool used by engineers to design and plan for the physical creation of a 3D object. The way in which the 3D product model has been applied to production and assembly processes has evolved over time, yet the current body of knowledge does not document that evolution. The purpose of this article is to collect and structure the evolution of 3D product model research, categorizing the ways in which the body of knowledge has evolved over time, while also providing a look into projected applications and research focuses of the 3D product model. The result of this article is the development of sixteen 3D product model research themes and the categorization of the body of knowledge within those themes, establishing a basis for 3D product model research ontology. Then, the paper explores where the evolution of the 3D product model is trending based on discussions with industry experts. The authors aim to provide a foundation for a comprehensive and interdisciplinary discussion amongst academia and industry about the current state and future trends of research on the 3D product model and its application in production and assembly processes.

Keywords

Assembly; process planning systems; concurrent engineering; automotive industry applications; manufacturing industry applications

Introduction

Three-dimensional (3D) product models generate value to manufacturing companies in multiple stages of the engineering, assembly, and production processes [1]. Initially used primarily as a design tool, the 3D product model focused on helping engineers create visual models of the product they intended to create. The 3D product model later moved into the production and assembly processes, helping create value in a variety of ways, from allowing operators to see how a product is configured to ensuring the right parts, tools, work instructions, and other critical components are assigned to the right stations [1,2]. With the development of new software and technologies, the stage is now set for the 3D product model to be utilized in emerging applications and frontiers of industrial and systems engineering [3,4]. The authors note that the 3D product model can have a large array of meanings from the virtual computer-aided design (CAD) model, to a digital mock-up, to a digital twin, or even a physical 3D model. The 3D product model application focused on in this paper is the value of bringing the virtual CAD model and digital 3D assembly mock-up to the assembly process beyond the engineering design. The authors have recognized that the 3D product models usability has increased as computer graphics have improved, mathematical models have emerged to simplify the 3D product model representations, and technology such as virtual reality glasses provide new 3D product model applications. As concepts such as artificial intelligence, robotics, and the digital twin emerge in both academia and industry, the authors aimed to understand the 3D product models role in these evolving applications. Doing so led the authors down a path of reviewing how the 3D product model research has developed to date, which was followed by interviewing industry experts on anticipated future trends.

The authors recognized a significant amount of research in the body of knowledge on 3D product models with similar focus topics but did not come across any research that established themes around these topics and categorized the research accordingly. This generated the question "How has the 3D product model research evolved over time?" and, once these themes were determined, "Where is the research and industry applications of the 3D product model projected to head in the future?" The authors' intent is to answer those questions and close the current gap in the research, providing the foundation for future comprehensive 3D product model research ontology. This work collects a comprehensive list of approximately 300 articles and conference proceedings that discuss the 3D product model and its applications to assembly and production processes, develops themes across the research, categorizes the research by those themes, and projects future applications and research trends.

Materials and Methods

The schematic of the research methodology used in this research is shown in Figure 1.

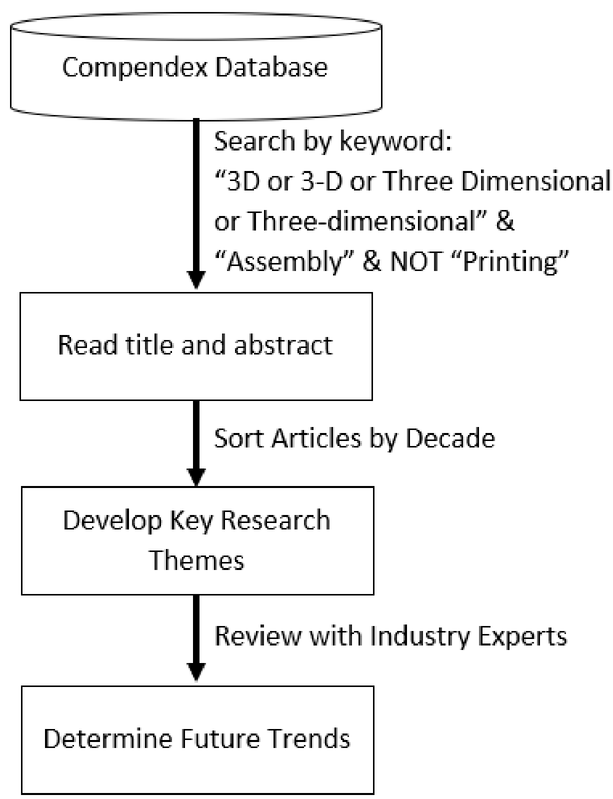

Figure 1. Schematic of research methodology

The research team searched the Compendex database for articles that contained any variation of the term "3D" and "assembly" while excluding "printing." The objective of this search was to identify the body of literature in the engineering field that focused on 3D product models and their application in assembly operations. This search generated over 40,000 relevant database entries and, when limited to English, resulted in 38,934 records. When limited further to journal articles, the search results in approximately 24,690 records. To view how the magnitude of research on the 3D product model has evolved over time, the authors sorted the research entries by year, as show in Figure 2. While there were articles written on the 3D product model prior to 1970, the number recorded in the database was minimal, and the authors have excluded them from the figure to make the remainder of the figure large enough to be legible. That said, the articles that predate 1970 have been considered in our analysis.

Then, the authors reviewed the title and abstracts of the journal articles returned in the search. Given the intent of this research was to review how the 3D product model research has evolved over time, the authors started with the oldest research articles and began to comb through them to identify research trends. As the authors progressed, the team was able to determine additional search terms that could be excluded to reduce the quantity of articles to review without eliminating large swaths of the body of knowledge that would be applicable to the research. The term "printing" was excluded to remove the research surrounding 3D printing, as the authors were primarily focused on the application of 3D product models in manufacturing facilities requiring production and assembly operations.

The authors do note that the 3D product model has a direct tie to the 3D printing application, as the 3D product model is the foundation of 3D printing and even computer numerical control (CNC) milling and machining techniques. While 3D printing and enhanced machining capabilities are a key component of the 4th industrial revolution and do tie back to the 3D product model, the authors' aim in this research was to focus on the assembly process. While in some cases, enhanced 3D printing and machine techniques can be used to replace the need for assembly altogether (given that complex shapes and geometries can now be produced as a single component, which was not previously feasible), there are still a large number of applications where assembly is critical. Such applications include assemblies of complex equipment in industries such as motor vehicles, industrial machinery, aerospace, medical products, construction and farm machinery, and electronics. These industries are the primary focus of this research, which is why the authors have chosen to exclude "printing" as a search term, to target the research to those industries that involve complex assembly operations. For readers who are interested in learning more about 3D printing and its role in industry 4.0, the authors included some supplemental references [5–7].

To remove research surrounding 3D fluid flows that are not applicable to the application of 3D product models in assembly operations, the terms "convection, laminar, petroleum, thermal, and thermo" were added to the list of excluded terms. Likewise, the words "carbon, chemical, chemistry, nuclear, and nano" were excluded as the research with those terms tended to focus on 3D molecular structures. The final excluded terms added were "structural and semiconductor", as the authors were primarily interested in the application of 3D product models to products that would be produced in a manufacturing facility with size and scale requiring production and assembly processes, versus application to building structures or electrical components. These excluded terms were developed based on the authors' initial review of the data to determine segments of research that the database query was returning that were not applicable.

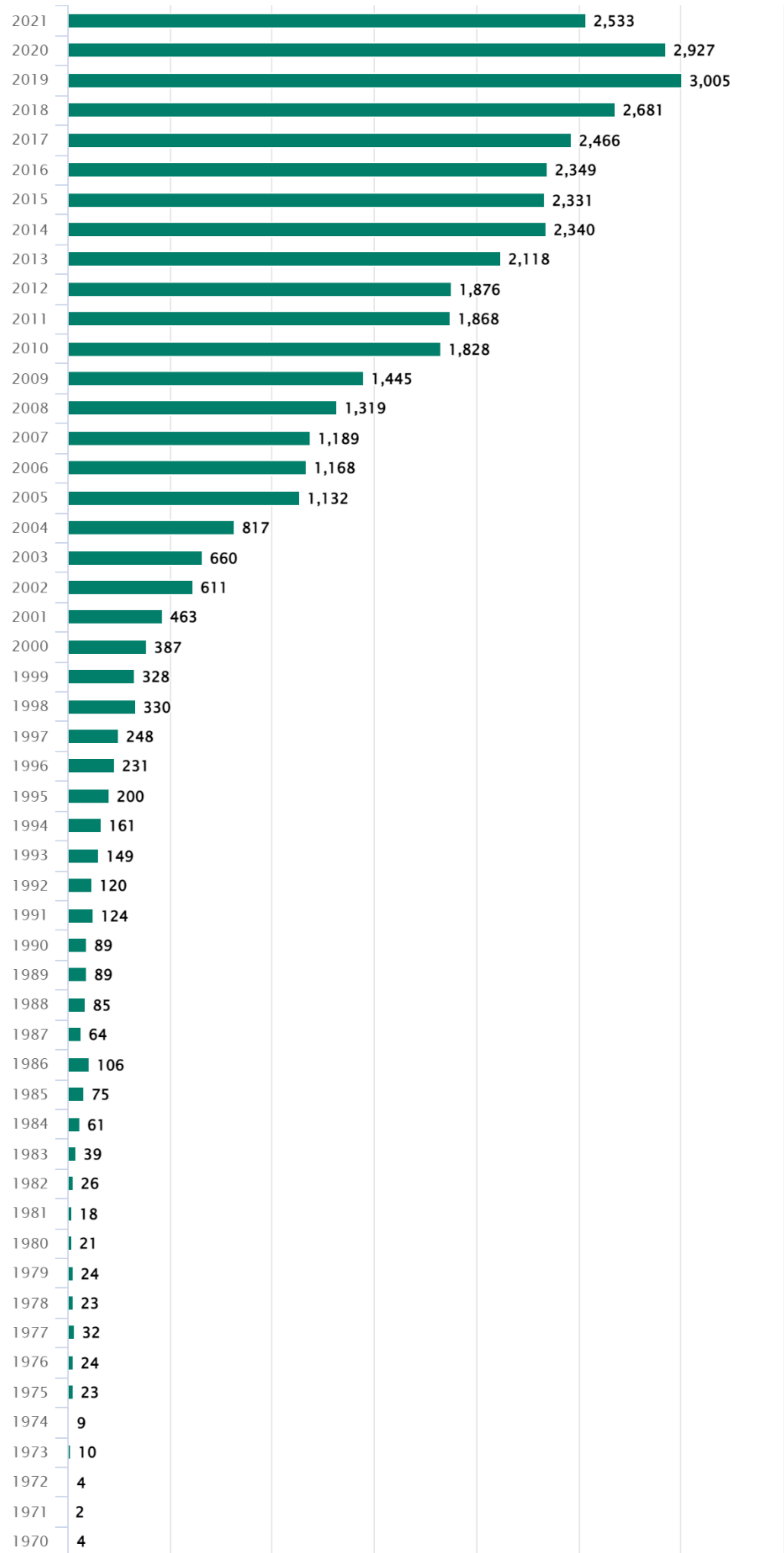

Figure 2. Compendex research records on the 3D product model with an assembly reference over time

The exclusion of the terms shown above reduced the records to closer to 4000. These were broken down by decade, as shown in Table 1.

Table 1. Three-dimensional (3D) product model journal articles in English from Compendex records by decade.

Decade(s)	Compendex Journal Article Records	Compendex Records (Limited by search terms)
1940's – 1960's	24	20
1970's	5	1
1980's	188	99
1990's	957	354
2000's	4,662	943
2010's	14,428	1,824
2020's	4,416	501
Total	24,688	3,742

Then, the authors reviewed the remaining articles and summarized the key findings in those that are relevant. Not all records that remained after the search terms noted above were relevant, so the authors spent a great deal of time reviewing the remaining records to capture the research work applicable to the evolution of 3D product model research over time. The results are presented in the next section.

Results

In reviewing the body of literature of the 3D product model research, the authors developed the following themes that the research focused on around the 3D product model. These themes and the corresponding number of applicable research papers that reference them are noted in Table 2.

Table 2. Three-dimensional (3D) product model research themes and associated number of references.

S. no	3D Product Model Research Themes	# of Reference(s)
1	Product Design	37
2	Design for Assembly	21
3	Data Processing	22
4	Geometric Dimensioning & Tolerancing (GD&T)	34
5	Assembly Sequence Planning	34
6	Virtual Assembly/Virtual Reality (VR)	27
7	Assembly line/Station layout planning	24
8	Interpolation between 2D & 3D Models	10
9	Reverse Engineering/Scanning Technology	7
10	Assembly Feasibility	4
11	Web Based Applications	14
12	Virtual Training/Work Instructions (WI)	13
13	Augmented Reality (AR)	21
14	3D Model Library	13
15	Disassembly	3
16	Artificial Intelligence (AI) & Digital Twin	8
Total		292

To provide additional visibility into how these research themes were developed, the authors have listed the research articles and conference proceedings that were used to determine these research themes. Given all these articles and conference proceedings are being referenced simultaneously in Table 3, the authors chose to list the references in alphabetical order by last name in the References section. It is of note that the authors chose to assign one research theme per publication and thus selected the most prominent theme.

Table 3. Three-dimensional (3D) product model research themes and associated references [8–299].

S. No	3D Product Model Research Themes	Reference(s)
1	Product Design	[11,12,14,15,21,24,27,41,42,46,65,67,72,76,81,84,100, 102,106,114,134,139,172,176,195,196,212,215,216,221, 232,243,244,253,270,274,275,277]
2	Design for Assembly	[16,19,22,30,58,82,98,116,120,155,163,181,183,192,204, 211,220,260,267,273,289]
3	Data Processing	[9,62,95,111,113,149–151,173,175,185,207,217,233–235, 276,280,282,283,285,287]
4	Geometric Dimensioning and Tolerancing	[17,29,50,69–71,74,77,91,105,122,143,154,156–158,164, 167,198,200,201,208,210,223,227,238,239,242,247,251,261,291,294,298]
5	Assembly Sequence Planning	[32–39,57,59–61,79,90,98,99,117,126,128,130,140,146, 165,171,190,209,225,229,237,240,245,246,259,297]
6	Virtual Assembly/Virtual Reality	[18,43,45,53,75,93,96,109,110,119,123,125,133,152,197, 214,222,224,231,250,254,258,279,286,295,296,299]
7	Assembly line/station layout planning	[10,25,40,44,47,78,80,83,86,87,92,135,147,153,169,182, 194,202,228,236,252,256,257,271,272,288]
8	Interpolation between 2D and 3D Models	[8,28,85,168,213,219,248,255,263,278]
9	Reverse Engineering/Scanning Technology	[20,48,66,118,199,230,262]
10	Assembly Feasibility	[13,129,144,218]
11	Web-Based Applications	[52,63,64,68,131,132,148,160,161,191,205,241,266,269]
12	Virtual Training/Work Instructions	[26,49,51,112,127,141,174,177,178,187,189,226,281]
13	Augmented Reality	[55,56,73,88,89,97,115,145,162,170,179,186,188,193,206, 258,264,265,268,292]
14	3D Model Library	[54,121,122,136–138,142,166,180,184,203,284,290]
15	Disassembly	[23,94,104]
16	Artificial Intelligence and Digital Twin	[31,101,103,107,108,159,249,293]

While Table 3 provides the research corresponding to each 3D product model theme, it does not show a clear visual of the research evolution over time. The authors also developed how the 3D product model research evolved by decade, as shown in Figure 3. The themes over time and the amount of research in each decade can be combined to then find what the major themes were for each decade of research. Table 4 demonstrates the research in quantity of research articles by research them by decade over time.

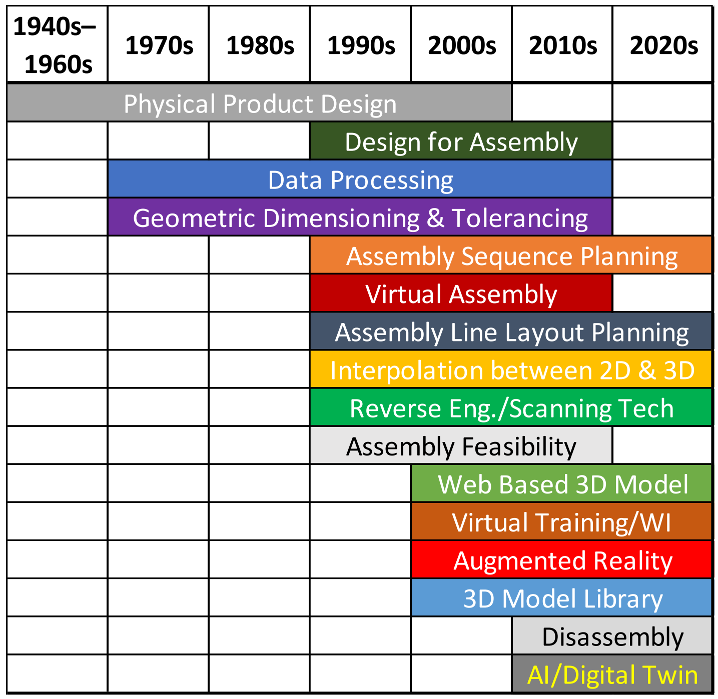

Figure 3. Three-dimensional (3D) product model research themes evolution over time.

Table 4. Three-dimensional (3D) product model research themes evolution with journal article count.

S. No	3D Product Model Research Themes	1940s–1960s	1970s	1980s	1990s	2000s	2010s	2020s
1	Product Design	3	4	12	15	3		
2	Design for Assembly	3			2	15	1	
3	Data Processing		2	6	1	2	11	
4	Geometric Dimensioning and Tolerancing		1	3	1	11	15	3
5	Assembly Sequence Planning			1	2	9	21	1
6	Virtual Assembly/Virtual Reality				6	11	10	
7	Assembly line/station layout planning				7	6	8	3
8	Interpolation between 2D and 3D Models				2	4	3	1
9	Reverse Engineering/Scanning Technology				2	1	3	1
10	Assembly Feasibility				1	2	1	
11	Web-Based Applications					9	4	1
12	Virtual Training/Work Instructions					2	9	2
13	Augmented Reality					2	12	7
14	3D Model Library					1	11	1
15	Disassembly						3	
16	Artificial Intelligence and Digital Twin						1	7

As the data show, the 3D product model started as a tool mainly used for product design all the way through the 1990s. In the 1990s, virtual reality and virtual assembly began to be discussed, along with the idea of using the 3D model beyond just product design for applications in assembly line and assembly station layout planning.

In the 2000s, the research focus shifted from just designing the product to also designing for assembly. The importance of how 3D product models could assist in geometric dimensioning and tolerancing increased, and the use of 3D product models in virtual environments gained further traction. The 2000s also showed the start of research on how the 3D product model could be used in web-based applications, and early discussions on moving beyond virtual reality to augmented reality began.

In the 2010s, the importance of structuring the 3D product models so that the data within them could be more easily processed by computers began to take off. While virtual reality and virtual assembly applications of the 3D product model remained strong, augmented reality and combining the virtual and physical environments gained traction. In addition, with the further development of more 3D product models, the need arose to reduce redundancy in creating 3D product models, and research grew on how to query databases of 3D product models to find already designed parts and assemblies. Deploying the 3D product model to the shop floor via virtual training and virtual work instructions was also a research topic that garnered support.

In the 2020s, the concept of the 3D product model applications has seen another shift. While augmented reality remains a relevant topic, much of the research has moved to the application of the 3D product model in artificial intelligence and digital twins.

The authors' development of the sixteen 3D product model research themes and the categorization, by decade, of the body of knowledge into those themes answers the question of how the 3D product model research has evolved over time. Then, the 3D product model research themes developed in this work provide the foundation for a future comprehensive 3D product model research ontology.

Discussion

The 3D Product Model Research Evolution

As seen in the Results section, the authors were able to develop 3D product model research themes and identify trends in those research themes over time. These trends will be discussed in greater detail, with specific examples throughout the Discussion section of this paper.

1940s to 1960s

In the 1940s to the 1960s personal computers were not yet in existence, and so while companies and individuals were developing engineering drawings, they were doing so by hand. Many of the engineering drawings were done in two dimensions but, even before the existence of a personal computer to aid in 3D product model development, companies were still finding applications for the development and use of 3D models. In 1941, Douglas Aircraft was using hand-drawn three-dimensional drawings to speed up the planning and operation of their mass production assembly lines, and by 1942, Boeing had begun doing the same [76,253]. In some instances, a miniature physical 3D model of the plant and the product were being developed, such as at Ford Motor Company in 1947 followed by other organizations in the 1950s [16,196].

1970s

In the 1970s, the research remained largely focused on using the 3D product model for product design. That research included a range of applications from how 3D product models could be used in the design of a diesel engine to the design of buildings [114,215,216]. In addition, the American Society of Mechanical Engineers published research that was the first of its kind to account for tolerances and dimensioning of 3D models [77]. Research also began on how databases can be used to capture the information that a 3D product model contains [113].

1980s

In the 1980s, again, the focus of the 3D product model research remained on product design, with many large organizations concentrating research efforts in this area, including research sponsored by organizations such as IBM, Austin Rover, McDonnel Douglas, and Northrop Aircraft [27,139,221,274]. However, the research also built on the trends started in the 1970s of 3D product model geometric dimensioning and tolerancing as well as data processing of the 3D product model. Organizations that were focused on the data processing of the 3D product models and reviewing the ways in which users wanted to access the 3D product model data included IBM, Princeton, and Combustion Engineering [111,235,280]. In the same decade, both John Deere and Eastman-Kodak focused research on geometric dimensioning and tolerancing of 3D product models to statistically analyze tolerance stack-up and develop probability information on how assembly dimensions are distributed when parts are assembled [74,208,227]. The 1980s also saw the first development of research focused on moving beyond the product design focus to include the impact the 3D product model has on the assembly sequence [140].

1990s

While product design continued to be the focus of the 3D product model research in the 1990s, the emergence of new technologies enabled research to begin on virtual assembly and using the 3D product model in virtual environments. The research on the virtual assembly of 3D products included the implementation of force feedback systems from the virtual environment to the physical environment at the Institute of Technology in Japan, combining human movement in the assembly of 3D products in the virtual environment with ergonomics research at Caterpillar and using the virtual environment for virtual assembly training at Motorola [75,110,279]. The virtual environment and 3D product model were also used at Iowa State University's Virtual Reality Applications Center to identify the impact that part shapes have on the stresses on that part and make modifications in real time [222]. Technology and research also emerged in the 1990s to not only apply the virtual environment to the physical world but also reverse engineer the physical world into the 3D virtual environment. Scanning technologies and coordinate measuring machines (CMM) were used to capture key data points of physical objects and translate them into 3D models [66,118].

2000s

In the 2000s, the research shifted from the 3D product model design to 3D product model design for assembly. Research emerged on computer-aided assembly planning systems, with applications ranging from electromechanical components to pumps, torque converters, golfcarts, and aircraft [30,82,163,183,192]. As research on design for assembly grew, so did the use of the 3D product model for virtual assembly training and the development of virtual work instructions [187,226]. On the research front of geometric dimensioning and tolerancing of 3D product models, the literature moved beyond applying probabilities to tolerance stack-up to determining the optimal configuration of variant part assemblies, in addition to the tradeoffs between improved tolerances and associated costs that were reviewed in the 3D product model development stage [124,156]. The functionality of the internet and world wide web also improved greatly in the 2000s, and with that came research on how to deploy 3D product models over the web, with the development of the virtual reality modeling language (VRML) aimed at meeting that objective. With the advent of VRML, researchers looked to increase its functionality via proposing solutions such as concurrent design environments, drag-and-drop applications, and manufacturing task planning over the web [64,205,269]. This technology enabled different individuals located in different locations around the world to simultaneously work on and edit the same 3D product model. In the 2000s, the first research on augmented reality using the 3D product model also emerged, with early applications including the evaluation of assembly sequencing and prototyping using both physical and virtual models simultaneously [179,193].

2010s

From the 2000s to the 2010s, the research on 3D product models continued to accelerate. Key focus areas of that research included enhancing the ability of the 3D product model data to be processed by computers, the need to catalogue 3D product model parts in a library for reference-and-reuse versus recreation, and a larger focus on augmented reality applications. To enhance 3D product model data processing, compression algorithms were developed, mesh segmentation of the 3D model was utilized, and programs were developed to convert 3D product model file formats to standardized formats [62,207,285]. Model-based definition structures and lightweight 3D models were also developed to enhance data processing [94,95,233,234]. As more 3D models are developed, the need began to arise for a library of 3D product models that could be referenced and reused rather than recreated. Research on ways to achieve the reuse of existing 3D product models from 3D product model libraries included assembly-based modeling, 3D CAD assembly model matching, and a significant subassemblies approach [54,137,138,290]. In the 2010s, the application of augmented reality also spread across and intertwined with other research categories of the 3D product model, including design for assembly, assembly planning, and disassembly [55,186,268].

2020s

While, at the time of this writing, we are still early in the decade of the 2020s, the 3D product model research has evolved to focusing on the application of the 3D product model in artificial intelligence, robotics, and the digital twin. The 3D product model is at the confluence of these areas, being applied to robotic assembly via digital twin technology and serving as a digital representation of the physical space on a real-time basis [103,159]. The 3D product model also continues to be applied in augmented reality applications, with recent research focused on user cognitive load and user satisfaction when utilizing these Industry 4.0 augmented reality applications [170].

The 3D Product Model Research Current State and Future Trends

In discussions with industry experts, as we move through the 2020s into the 2030s and beyond, a number of trends are anticipated to play out in 3D product model research and industry applications. As organizations evolve and enterprise architecture interdisciplinary teams develop, the application of the 3D product model and the information they contain will become more broadly available beyond segregated departments such as information technology or operations. This will enable a federated approach in which having the 3D product model data will better enable teams to autonomously make decisions needed to reach the organization's key objectives. The standardization of data methods across industries will be a key enabler of this autonomy and accelerate the adoption of the 3D product model in areas such as analytics, machine learning, and the internet of things (IOT). The 3D product model will move from an analytic tool to becoming an integral part of the product lifecycle, where the evolution of the geometry and key characteristics of the product will also be able to be modeled in real time as the product moves through the production process.

Knowing the evolution of the part geometry through the production process will enable marrying the product digital twin with the process digital twin and create opportunities such as knowing what products are best to be ordered based on machine set-up, calibration, and dimensions for less changeover time via the sequencing of similar parts. The marrying of the product digital twin and process digital twin will also help mine out manufacturing patterns to generatively create designs and help determine the best manufacturing processes for a given 3D product model geometry. In addition, marrying the product digital twin with the process digital twin can be coupled with the use of neural nets to reduce individual stock-keeping units (SKUs) through providing recommendations on 3D product model parts to combine based on both geometry and the manufacturing processes used to create them. As new parts are designed, the computer will also be able to provide design recommendations based on previously developed 3D product model parts clusters. This evolution combines product design with design for assembly and design for manufacturability.

Over time, machine learning will be able to be used to associate manufacturing operations to the engineering 3D product model design. Any two parts that come together are joined somehow, and the computer will learn to determine how those geometries should be manufactured and assembled, including what tooling to use to do so. Machine learning of the 3D product model will also enable the development of numerical control (NC) program generation, and inspection plans will be automatically generated that are needed to manufacture, assemble, and inspect a part/assembly. Such developments will require parallel computation and quantum computing to account for the correlation and make such solutions possible.

Eventually, the sustainability and repurposing of material will also become a cognizant component of the 3D product model design. The design, manufacturing processes, and operations will be done in such a way to allow that product to be easily upgraded and/or reused in different ways for subtle tasks.

Conclusions

The 3D product model opens a vast array of possibilities, from how the product is designed to how it is manufactured assembled, transported, serviced, and re-used. This article identified research themes in the 3D product model research evolution, categorized the research by those themes, and provides a look into the future on 3D product model research that is currently under development and yet to come. Overall, 16 research themes were identified, including applications of research on how the 3D product model fits into emerging frontiers such as artificial intelligence, robotics, and the digital twin.

The major research themes were identified in a one-to-one relationship between the research themes and the literature. Future research could evaluate a one-to-many relationship in which the literature is assigned multiple research themes, to add additional context around the 3D product model research evolution. In addition, this research used Compendex as the database of record, so other sources (such as Scopus) could be used to further evaluate and expand the body of knowledge and research themes collected in this work. Many of the research themes were listed in the literature, but definitions on these research themes were not always explicitly provided. Thus, the research themes in this work are based on the knowledge, expertise, and perspectives of the authors. The authors aimed to increase the transparency of the research theme development by sharing the previously published research that applied to these themes. The authors encourage others to provide feedback and challenge the selection of the research themes and projected future trends.

Author Contributions

C.K. and G.H. conceived the idea. C.K. formulated the problem, developed the research themes, and worked with industry participants to determine probable future research trends. G.H. and D.S. provided guidance throughout the research and proofread the manuscript. All authors have read and agreed to this version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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CHAPTER 4. VALUE OF THE 3D PRODUCT MODEL USE IN THE ASSEMBLY PROCESS: PROCESS PLANNING, DESIGN, AND SHOP FLOOR EXECUTION

Carl Kirpes, Dave Sly, and Guiping Hu

Industrial and Manufacturing Systems Engineering (IMSE), Iowa State University

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Abstract

Organizations can enhance the value of their assembly planning, assembly design, and assembly shop floor execution through the use of the 3D product model. Once a tool targeted at product design, the 3D product model, enabled by current and emerging manufacturing process management technologies, can create additional value for organizations when used in assembly processes. The research survey conducted and described in this paper demonstrates the value organizations have seen in using the 3D product model in the assembly process. The paper also explores the current state of those organizations who have not yet implemented the use of the 3D product model in their assembly processes and the value that they foresee for possible future implementation. The essential findings of this research are the five qualitative areas in which value is derived from using the 3D product model in complex assembly processes and how those value drivers apply across various industries and organization sizes. These results provide a framework for future research to develop quantitative models of the value of the 3D product model use in assembly processes.

Keywords

Assembly; Process Planning Systems; Concurrent Engineering; Automotive Industry Applications; Manufacturing Industry Applications

Introduction

The first adoption of 3D product models among the engineering disciplines was in product design. Whereas 2D drawings previously required engineering expertise and an object-oriented mindset to imagine a 3D object based on the shapes depicted, the 3D product model provides a non-engineering trained person with the same opportunity to visualize the product before it is built. Such functionality is of great benefit as engineers work on the design of the product with marketing, sales, suppliers, potential customers, and other functions inside and outside of the organization. However, if the use of the 3D product model stops at the design phase, the benefit of the 3D product model is not fully realized.

To better understand the value of the 3D product model in the assembly process, a literature review was conducted. Journal papers, articles, and conference papers were sourced using the Compendex and Scopus databases. Articles searched for included reference to "3D" and "assembly" but not "printing" (in order to remove articles on 3D printing, which is not the focus of this study). Then, an analysis was run on the number of times these key words were used throughout the article. Noting that some articles are longer than others, the total count was divided by the article page count to get an understanding of the density of the use of the "3D" and "assembly" keywords in each article. Each article was also reviewed for mentions of the value that using 3D product models in the assembly processes could create. Such value might include improving the efficiency and reliability of the assembly process design, reducing process planning problems, and shortening the process planning cycle [1,2]. Then, the same approach was taken in terms of dividing the number of mentions of value creation by the total page count to get a density value for value creation mentions in each paper. The plot of these relative densities of "3D" to "assembly", where "value creation" is the size of each bubble, is shown in Figure 1 [1–34] where each different colored bubble represents a different journal paper, article, or conference paper. Figure 1 demonstrates that while there was a lot of research published on 3D product models, and an equivalent amount published on assembly processes, less literature had been published on the use of 3D product models in assembly. This was especially evident in the lack of data points in the upper right corner of Figure 1 and the fact that of those papers that do have a high density of “3D” and “assembly”, there is still a gap in the literature in terms of the value that the use of 3D product models creates in assembly processes. Exploring this gap and better understanding the value that 3D product models create in the assembly process provided the guiding purpose for this research.

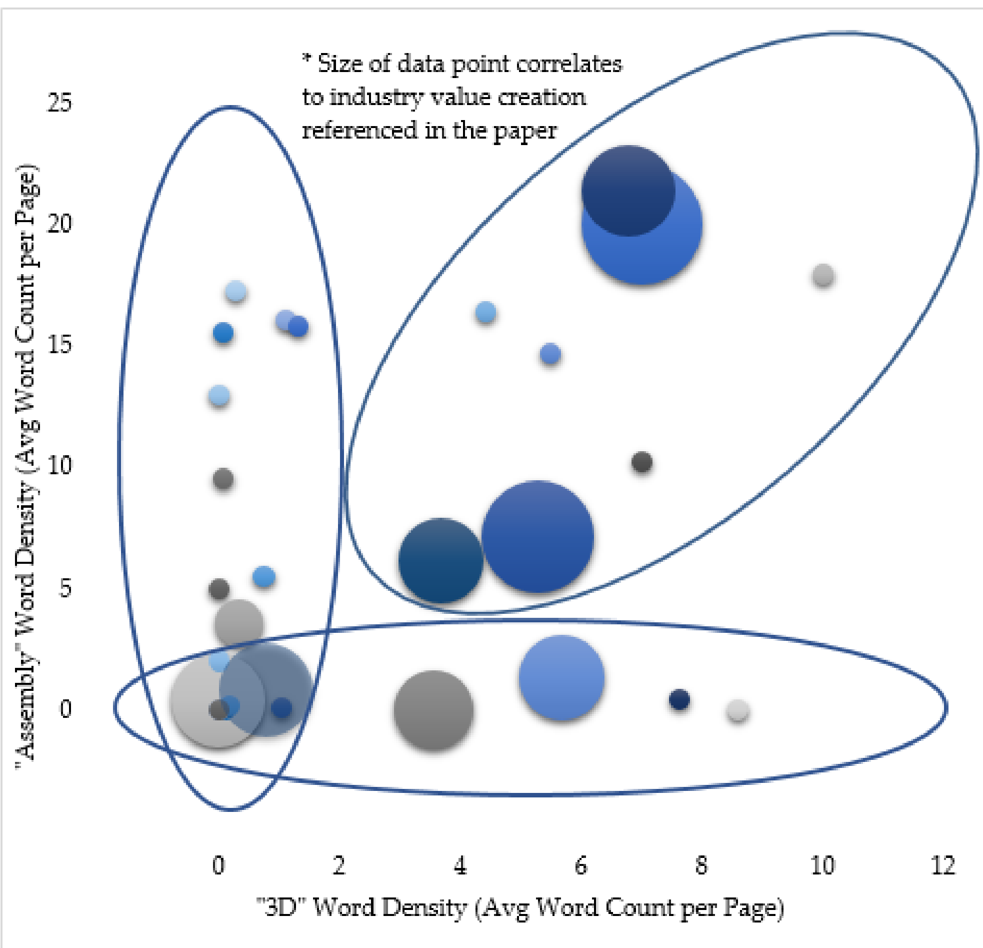

Figure 1. 3D product model in the assembly process: literature review.

The ability to capture the value that 3D product models create in assembly processes has been limited by the availability of software to bring the 3D product model to the assembly processes [3,4]. Enabling factors including innovative education and training along with data-sharing systems and standards which have created an environment for technology to advance in such a way that smart manufacturing and the use of the 3D product model in the assembly process becomes feasible [5]. As such feasibility came to fruition, researchers and industry alike have found ways to transform the engineering bill of materials (eBOM) into the manufacturing bill of materials (mBOM) [6–8]; develop manufacturing process management software [9]; and extract 3D product model data and transfer it to virtual manufacturing and assembly software [10–15]. Researchers and industry also advanced this virtual assembly knowledge further, developing tools to automate assembly planning for complex products [16,17].

Once technology enabled the use of the 3D product model in the assembly process, research was conducted demonstrating how the 3D product model could be used in the assembly process planning, assembly design, and assembly shop floor execution processes (referred to in individual and in aggregate as “the assembly process” for the sake of brevity in this paper). This can be done by integrating the 3D product model with assembly line balancing via process consumption and leveraging the 3D product model in the link between the bill of process and the bill of materials including model/option dependency [18,35]. A similar approach includes the creation of a digital mock-up to transmit models and attribute data between the engineering bill of materials and the process (or manufacturing) bill of materials and serve as a unified data source in assembly planning [19]. By implementing such approaches, the use of the 3D product model in assembly processes allows for engineers to check the product’s configuration for assemblablity [20]. The 3D product model can also be used on the shop floor to enhance shop floor work instructions, improve process planning, and increase efficiency of assembly work [21,22]. Each of these studies indicate ways that companies can utilize the 3D product model developed by design teams in assembly processes. Given that some research has shown that such a feat is possible, then, the question becomes whether industry sees value in using the 3D product model beyond product design, and if so, in what areas industry believes value exists.

The objective of this research is to evaluate the use of 3D product models in assembly planning, assembly design, and assembly shop floor execution. The authors note that the 3D product model can have a large array of meanings from the virtual computer-aided design (CAD) model, to a digital mock-up, to a digital twin, or even a physical 3D model. The 3D product model application focused on in this paper is the value of bringing the virtual CAD model and digital 3D assembly mock-up to the assembly process beyond the engineering design. To illustrate an example, Figure 2 shows an assembly process where a fire truck is being built. Each octagon represents a station on the assembly line; some operations are completed by operators (the blue dots in the figure), and others are completed by robots. The operators have written work instructions which they use to know what parts to assemble and where to assemble those parts as different models and options of the fire truck progress down the assembly line. Figure 3 shows this same assembly line, but the written work instructions are replaced with 3D product models (virtual CAD models) of the part with visual assembly guidance. This is an example application of the 3D product model in the assembly process.

The paper explores the value organizations see in implementing the 3D product model in assembly processes. This paper will go through the methodology and results of a survey that was conducted to understand the value that organizations are seeing by implementing the 3D product model in assembly processes. The paper concludes with a review on the value of 3D product model use in assembly processes based on the survey results and a discussion on future research recommendations.

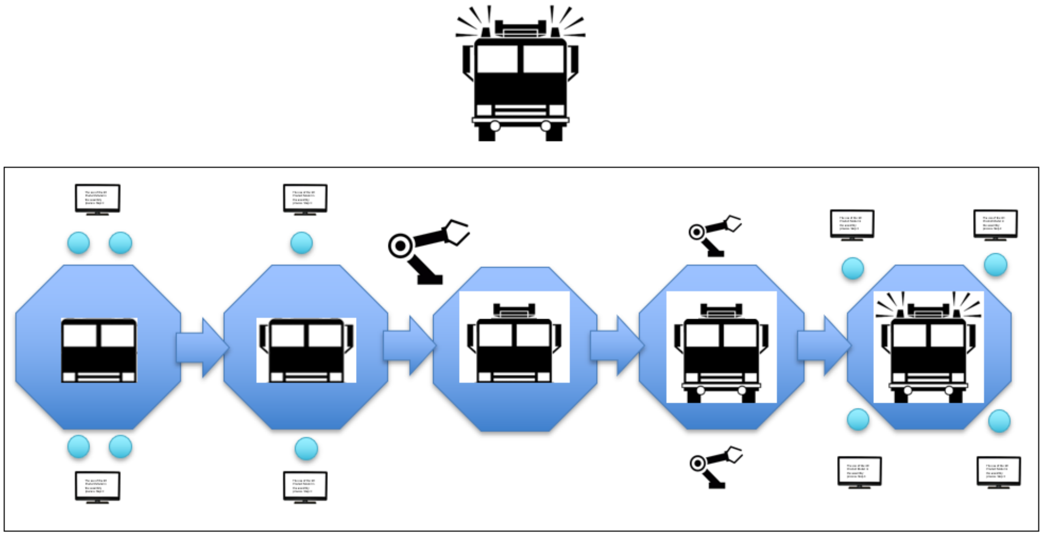

Figure 2. Assembly process using written work instructions.

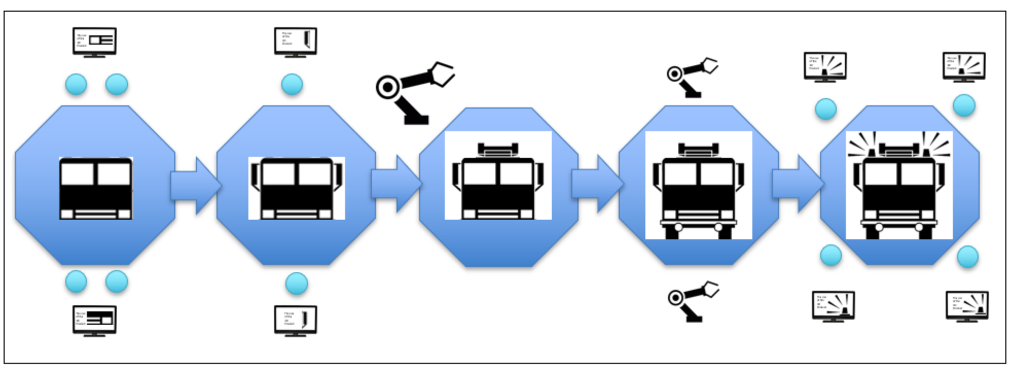

Figure 3. Assembly process deploying the 3D product model to the shop floor.

Materials and Methods

In this study, we adopt a survey to reach industry practitioners and understand if and how they have deployed the 3D product model in assembly planning, assembly design, and assembly shop floor execution processes. In addition, the survey aims to capture the value that the respondents have seen, or plan to see, in using the 3D product model in these assembly processes. The following are example survey questions developed accordingly:

(1) Please indicate your level of knowledge about the use of 3D product models in the assembly process, assembly design, or assembly shop floor execution at your organization:

  (a) Not at all knowledgeable

  (b) Somewhat knowledgeable

  (c) Knowledgeable

  (d) Very knowledgeable

(2) Has your company implemented 3D product models into the assembly process planning/design?

  (a) Yes

  (b) No

(3) Has your company implemented 3D product models into the assembly shop floor execution?

  (a) Yes

  (b) No

(4) To what extent does your company use 3D product models in the assembly process?

  (a) Screenshots of 3D model

  (b) 3D model mapped to process activities

  (c) 3D model mapped to parts consumption within process activities

  (d) 3D model fully integrated with Engineering Change Order/Manufacturing Change Order Process

  (e) Other (please describe):

(5) What technology is your company deploying to accomplish the use of 3D product models in the assembly process?

(a) Proplanner's Assembly Planner

(b) PTC's MPMLink

(c) Siemens Teamcenter

(d) Software developed in-house

(e) Other (please describe):

(6) What are the limitations of the technology your company is using to communicate the information contained in the 3D product model to the assembly team?

(7) If your company has implemented the 3D product model in the assembly process planning/design, what was your company doing before implementing the use of 3D product models for assembly process planning/design? (Select all that apply)

(a) Excel

(b) Simulation

(c) Paper/Post-It notes

(d) Physical mock-ups

(e) Other (please describe):

(f) Not applicable

(8) If your company has implemented the 3D product model in the assembly shop floor execution, what was your company doing before implementing the use of 3D product models in the shop floor execution?

(a) Virtual work instructions without the 3D product model

(b) Hard copy work instruction with 2D drawings

(c) Hard copy work instructions with pictures

(d) Work instructions without visuals, words only

(e) Operator training with no shop floor work instructions

(f) Other (please describe)

(g) Not applicable

(9) How did your company move from the former state to implementing 3D product models in the assembly process? (Select all that apply)

(a) Pilot study

(b) Wholesale cutover

(c) Started small and scaled implementation

(d) Other (please describe):

(10) What is the value your company has seen in implementing 3D product models in the assembly process? (Select all that apply)

(a) Accuracy of assignment of the right parts, tools, work allocation, and work instructions

(b) Faster new product/model roll out to production

(c) Less time updating work instructions

(d) Quicker operator training

(e) Other (please describe):

(11) What are the savings/estimated value/return (quantitative and/or qualitative) of implementing the use of 3D product models in the assembly process?

(12) What is the size of the company you work for?

(a) 1–999 employees

(b) 1000–9999 employees

(c) 10,000–49,999 employees

(d) 50,000+ employees

(13) What industry is your company a part of?

(a) Aerospace

(b) Agricultural Equipment

(c) Automotive (e.g., Light Car and Truck)

(d) Consumer Appliances

(e) Heavy Industrial (e.g., Heavy Equipment, Trucks, and Buses)

(f) Recreational Vehicles (e.g., Motorcycles, RVs, Four Wheelers, and Boats)

(g) Supply Chain

(h) Other:

(14) What is your title?

(a) C-level Executive

(b) Vice President

(c) Director

(d) Manager/Supervisor

(e) Engineer

(f) Other Individual Contributor

(g) Other:

To ensure these survey questions would be applicable to industry, the research team connected with a Manufacturing Process Management (MPM) software company. Discussions with the engineers and customer-facing employees in the organization allowed the research team to refine the questions around what level organizations were deploying 3D product model functionality in the assembly process planning, assembly design, and assembly shop floor execution; what the limitations were of the software used to deploy the 3D product model in the assembly process; and what plans the organization had for further deployment of the 3D product model in the assembly process. Using this framework, the research team came up with three categories that companies would be divided into based on their responses to the set of survey questions. These categories were (1) companies that had implemented the use of the 3D product model in the assembly process; (2) companies that had not yet implemented the use of the 3D product model in the assembly process but planned to; and (3) companies that did not plan to implement the use of the 3D product model in the assembly process. The later survey questions were tailored accordingly to fit within the context of the category an organization was classified into based on their responses to the initial survey questions, while still retaining the following overarching themes: what the company was doing before they implemented the use of the 3D product model in the assembly process, how that functionality was rolled out, what software was used, what the limitations are of that software, and what value the company was seeing or planned to see based on the use of the 3D product model in assembly processes. The research team used Qualtrics to develop and administer the survey. The survey hierarchy is shown in Figure 4.

The research team sent the survey out to individuals who were a specific subset of the population. Potential survey candidates were first screened based on the company that they worked for. Since the focus of the study is specific to companies that have manufacturing production and assembly operations, only individuals who worked for these types of organizations were included as potential survey respondents. As an example, an individual that worked for an automobile manufacturer or an agricultural equipment manufacturer would be considered a potential survey respondent, as organizations in those industries are engaged in assembling complex products and thus could use the 3D product model in the assembly planning, assembly design, or assembly shop floor execution processes. However, an individual who works at a hospital or a food/beverage company would not be considered a potential applicant for the survey. Those organizations do not have assembly as a part of their business processes and thus are not viable survey candidates. Including respondents that do not have assembly operations could skew the survey results, as those organizations would likely answer that they do not plan to implement the use of the 3D product model in the assembly process (simply because they do not have an assembly process through which to implement the use of 3D product models).

Once potential survey respondents were screened based on the industry in which they worked, they were then filtered down based on their role in the organization. For example, an engineer or director-of-operations is likely to have knowledge about the company’s plans or current use of 3D product models in the assembly process. However, an individual in accounting or human resources is likely not to have knowledge in that regard. As a result, if an individual worked for a company in an applicable industry, but was not in an applicable role, that individual was contacted in the context of providing an introduction to (or sharing the survey with) someone in their organization who was in an applicable role or was not sent the survey at all.

The research team started with a database of over 2700 contacts, which were filtered based on companies in applicable industries and individuals in applicable roles within those industries to 151. Of these 151, the research team found that the contact information was up to date for 85 individuals. These 85 individuals were provided with the link to take the survey on the value of the 3D product model use in the assembly process at their organization..

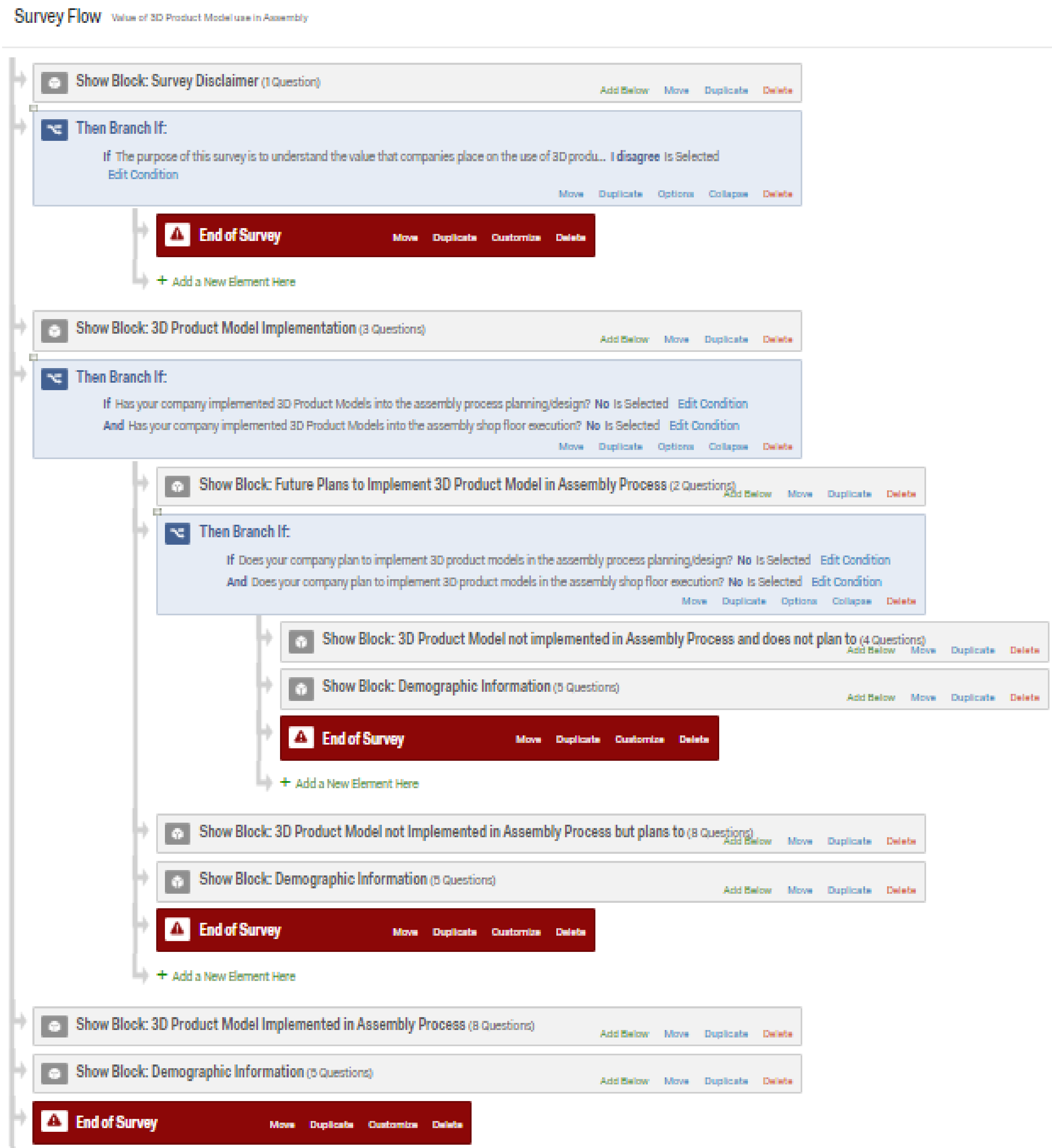

Figure 4. Survey flow hierarchy.

Of the 85 individuals sent the survey, 35 responded, equating to a response rate of 41%. Note that the date between when the survey was administered and the final data were collected was approximately one month. The number of respondents in the first week was 21; in the second week, it was 8, in the third week, it was 6, and in the fourth week, it was 0. The decreasing number of respondents and the fact that by the fourth week there were 0 respondents provided the research team with the indication that the majority of all respondents who were likely to respond had, and therefore, it was a good time to collect and analyze the data. The survey software was also set up to automatically record an individual’s response after two weeks of no activity on the survey. The objective of this being that if the survey respondent had answered the majority of the questions but forgot to click submit, as an example, then the survey information would be captured and of use in the analysis. However, this approach also led to some survey responses being logged where, as an example, the survey respondent had started the survey, answered the first couple questions, and then exited the survey. In such a case, not enough data were available for analysis. Of the 35 responses, 7 responses were removed prior to the detailed analysis due to survey responses getting recorded with too few questions answered for meaningful analysis.

Prior to analyzing the survey results, the research team’s hypothesis was that most companies would fall under the category of having not yet implemented the 3D product model in the assembly process but planned to do so in the future. This hypothesis was based on the research’s team review of the academic literature written on the topic, including the lack of papers that correlate the implementation of the 3D product model in the assembly process to the value such implementation creates for an organization. In addition, the research team conducted several meetings with an MPM software company to gain a further understanding of industrycapable 3D product model software functionality and limitations through the lens of this organization, which helped shape the hypothesis. Given the lack of literature discussing the value of the 3D product model in the assembly process, the research team also hypothesized that the value of using the 3D product model in the assembly process is expressed qualitatively and unknown quantitatively.

Results

Of the 28 survey respondents with enough data for analysis, the responses were categorized into three buckets as noted in the Materials and Methods section of this paper. A total of 23 respondents (82% of those analyzed) said that they have implemented the 3D product model in the assembly process. Note that assembly process means assembly planning and design and/or assembly shop floor execution. A total of five respondents said they had not yet implemented the 3D product model in the assembly process; of those, four respondents (14% of those analyzed) said they planned to implement the 3D product model in the assembly process, and one respondent (4% of those analyzed) did not plan to implement the 3D product model in the assembly process. This categorization of the survey responses is shown in Figure 5. It is worth noting that of the 23 respondents that implemented the use of the 3D product model in the assembly process, eight had implemented the use of the 3D product model in assembly planning and design but not shop floor execution, one had implemented the use of the 3D product model in shop floor execution but not assembly planning and design, and 14 had implemented the use of the 3D product model in both.

As discussed in the Materials and Methods section of this paper, potential survey candidates were screened based on the organization/industry in which they worked and their role within that organization to increase the likelihood that these individuals would have knowledge of the use of the 3D product model and how it was or was not being deployed in the assembly process in their organization. To test the effectiveness of the survey screening approach, survey respondents were asked to indicate their level of knowledge about the use of 3D product models in assembly planning, assembly design, or assembly shop floor execution. The categories and responses were as follows: very knowledgeable (6), knowledgeable (11), somewhat knowledgeable (5), not at all knowledgeable (1). With only one of the 23 respondents indicating that they were not at all knowledgeable about the use of the 3D product model in the assembly process, the survey screening approach appears to have been a success and drives greater confidence in the results described in this paper.

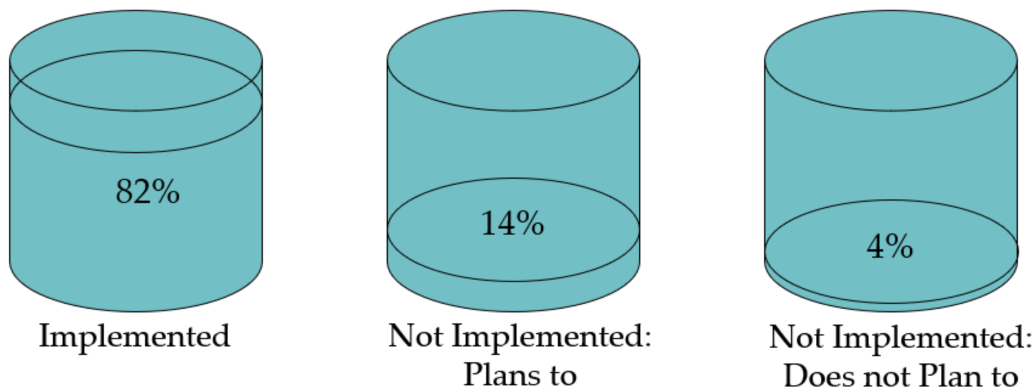

Figure 5. Categorizations of survey responses.

Company Has Implemented the 3D Product Model in the Assembly Process

To ensure that results were not biased by any one industry, the researchers checked the distribution of responses by industry type. As shown in Figure 6, there is a relatively even distribution of survey responses across multiple industry types, and all industry types have applicability to an organization in an industry that would be a candidate for the use of 3D product models in the assembly process. The authors note that when viewed as a group, the aerospace, agricultural equipment, and automotive industries comprise a large portion of the survey responses. Based on the authors’ experience, and comparison to the relative percentage of these industries to others with complex assembly operations on the 2020 Fortune 500 list (the largest 500 publicly traded companies in America by revenue), these three industries are a large portion of the population of the manufacturing organizations that have complex assembly operations. Of the Fortune 500 companies, only 44 companies are in industries that have complex assembly operations applicable to this research. Figure 7 shows the comparison of the percentage of survey respondents by industry relative to the percentage of companies with complex assembly operations by industry from the Fortune 500 and validates that the sample of industry respondents is representative of the broader population of manufacturing companies with complex assembly operations.

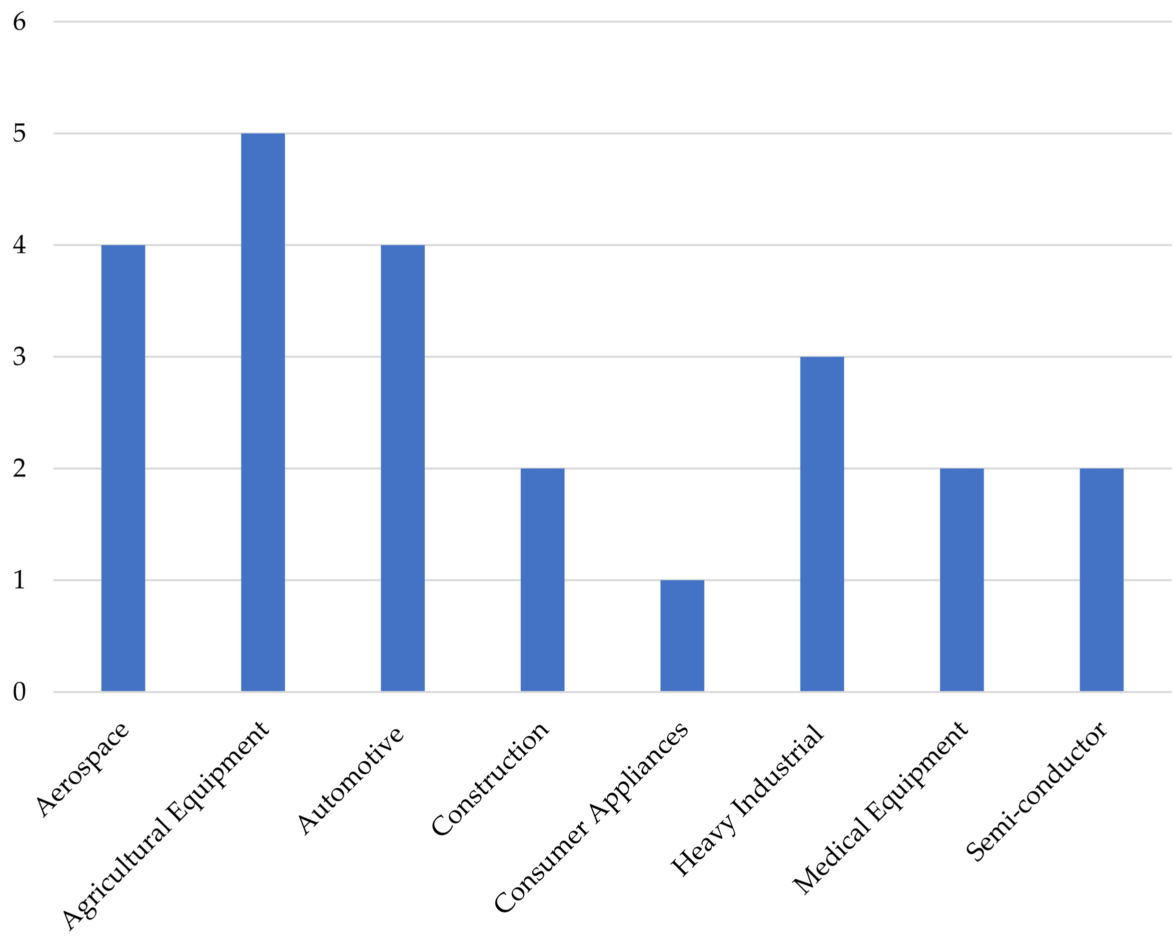

Figure 6. Industry distribution of respondents.

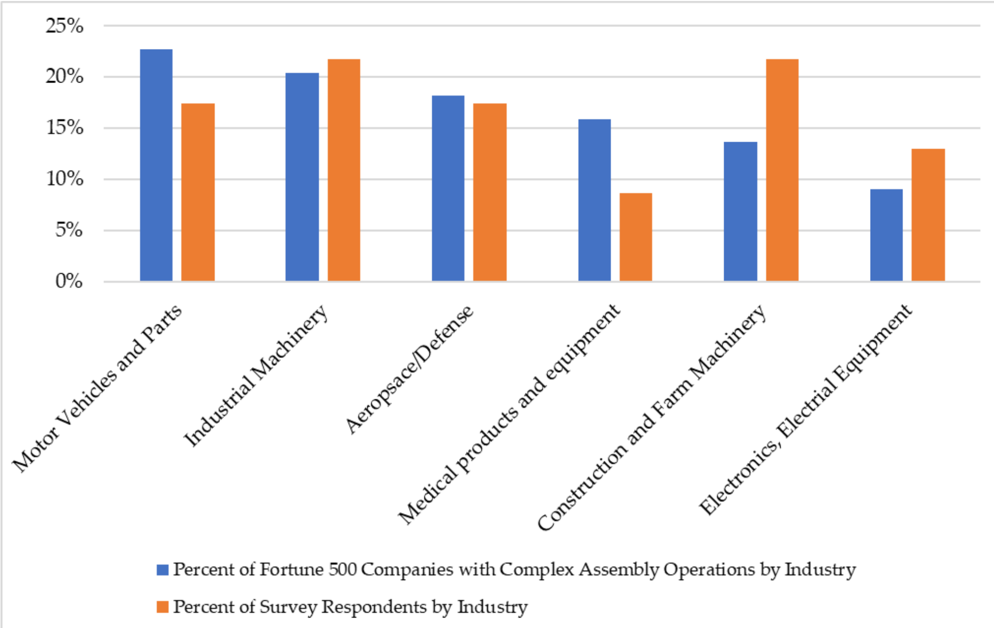

Figure 7. Comparison of survey respondent's percentage by industry to Fortune 500 companies with complex assembly operations percentage by industry.

In addition to ensuring that the industries represented by the survey respondents were reflective of the population, the research team also wanted to ensure that the jobs of the survey respondents within those organizations were representative of the population. Due to the nature of organizational hierarchies, there are more engineers than engineering managers/supervisors, more managers/supervisors than directors, more directors than vice presidents, etc. When reviewing the survey respondents, as seen in Figure 8, the categorization of respondents follows this general trend, which demonstrates that the survey responses are not biased by any one job type when compared to the broader population.

The research team also gathered information on the company size, by employee count, which was represented by the respondents. An interesting finding is that all respondents who worked for a large corporation said that their organization implemented the 3D product model in the assembly process. Figure 9 shows the breakdown of which size company the respondents work for based on employee count.

Figure 8. Job title distribution of respondents.

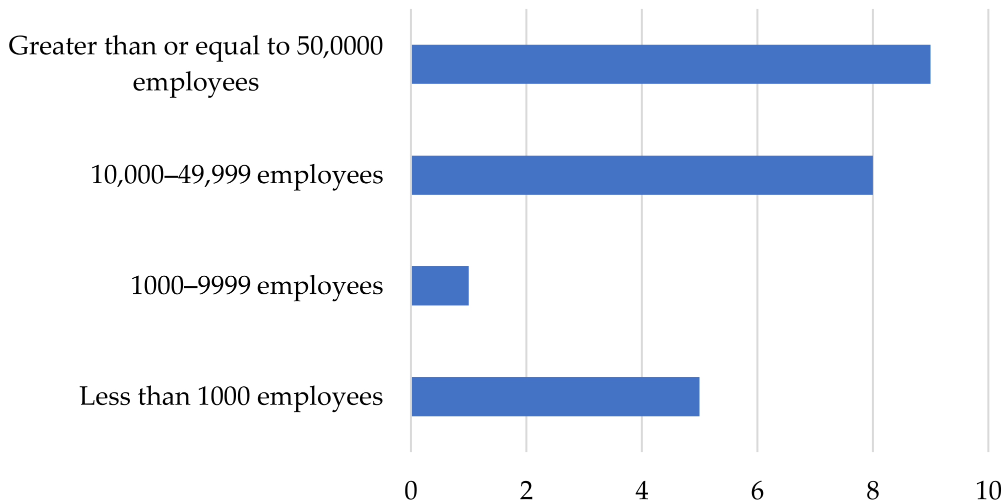

Figure 9. Company size based on employee count.

Noting that the majority of companies implemented the use of the 3D product model in the assembly process, further segregation into at which levels these companies implemented the use of the 3D product model in the assembly process is warranted. Figure 10 shows the responses in order of the most complex to least complex deployment of the 3D product model implementation in the assembly process.

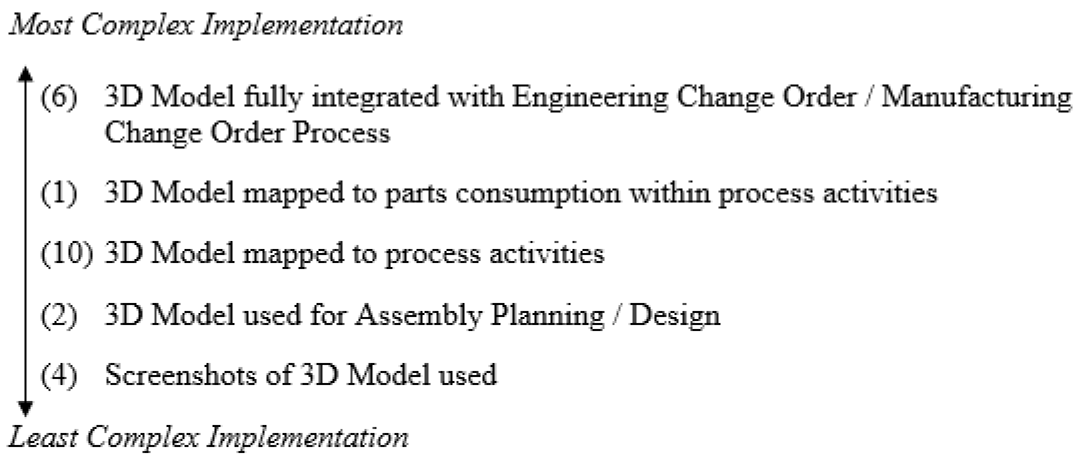

Figure 10. Extent to which 3D product models are used in the assembly process.

The software most commonly used to deploy the 3D product model was software developed in-house (nine total responses). The next two highest response counts for 3D product model software use in the assembly process were PTC's MPMLink (six responses) and Siemens Teamcenter (five responses). Although this demonstrates that technology is available on the marketplace today to use the 3D product model in the assembly process, the respondents did list limitations that these software currently face. In general, the responses show that the ease of use, the ability to handle revision/change control, and the integration with other software/processes were common limitations experienced by the software developed in-house and the software available on the market today.

Prior to deploying the software that allowed these organizations to use the 3D product model in their assembly process, the organizations relied on varying ways to communicate information contained in 3D product models to the process planning and design team. These included physical mock-ups (8), Excel (7), simulation (7), and paper/Post-It notes (4). Note that the sum of these responses (26) is greater than the number of survey respondents (23), as survey respondents were allowed to select more than one way in which this information was communicated prior to implementing the software that enabled the use of the 3D product model in the assembly planning/design. For those respondents who had implemented the 3D product model in the shop floor execution, they were also asked what they were doing to communicate the 3D product model information to the shop floor prior to their current state. All respondents to this inquiry shared that they used work instructions in some form to communicate this information; this included work instructions without visuals, words only (1), hard copy work instructions with pictures (3), hard copy work instructions with 2D drawings (6), and virtual work instructions without the 3D product model (6).

To transition to the 3D product model use in the assembly process, most organizations started small and scaled implementation (15), while some conducted a pilot study first (7). Only one respondent did a wholesale cutover to the 3D product model deployment and use in the assembly process.

Having the context of what companies were doing prior to implementing the 3D product model use in the assembly process and how they transitioned to their current state was important, as it provides insight for those organizations that have not yet implemented the 3D product model in the assembly process direction on how they might do so. However, more importantly is the value that the organizations have seen from implementing the 3D product model in the assembly process, as that is the incentive through which other organizations might consider doing the same. Figure 11 demonstrates that more respondents found value in the accuracy of assignment of the right parts, tools, work allocation, and work instructions relative to the other areas of value when implementing the 3D product model in the assembly process by a factor of more than 50%. This value driver was selected by over 60% of the survey respondents, and at 50% or greater of the total survey respondents at every level in the organization (engineering, manager/supervisor, director, and vice president). In addition, the accuracy of assignment of the right parts, tools, work allocation, and work instructions was selected by more than 67% of the participants across the aerospace, agricultural equipment, automotive, consumer appliances, and heavy industrial industries. These results indicate that the greatest potential for industry and academia to quantify the value of the 3D product model use in the assembly process is within the category of the accuracy of assignment of the right parts, tools, work allocation, and work instructions. Interestingly though, organizations with less than 1000 employees infrequently listed this value driver, meaning that developing models and quantifying the value for the accuracy of assignment of the right parts, tools, work instructions, and work allocation will likely be more beneficial to medium and large organizations. The results indicate that smaller companies would benefit greater by a model that quantitatively calculates the value of the 3D product model in the assembly process as it relates to faster new product/model roll out. The results also show that as the organization size increased, the number of value drivers indicated by the survey respondents increased. This points to larger organizations being able to better scale the deployment of the 3D product model in the assembly process and thus capture more of the value drivers accordingly.

Survey respondents further elaborated on the areas where they were finding value in the use of the 3D product model in the assembly process. Respondents shared comments on value gained such as “substantial”, “20:1”, and “multi-million-dollar savings in time to market”. Respondents shared that implementing the 3D product model in assembly processes “helps ensure no parts are forgotten in the work instructions for large, complex equipment” and created a “more efficient process for manufacturing engineers who develop the assembly process” and “reduced errors in assembly”.

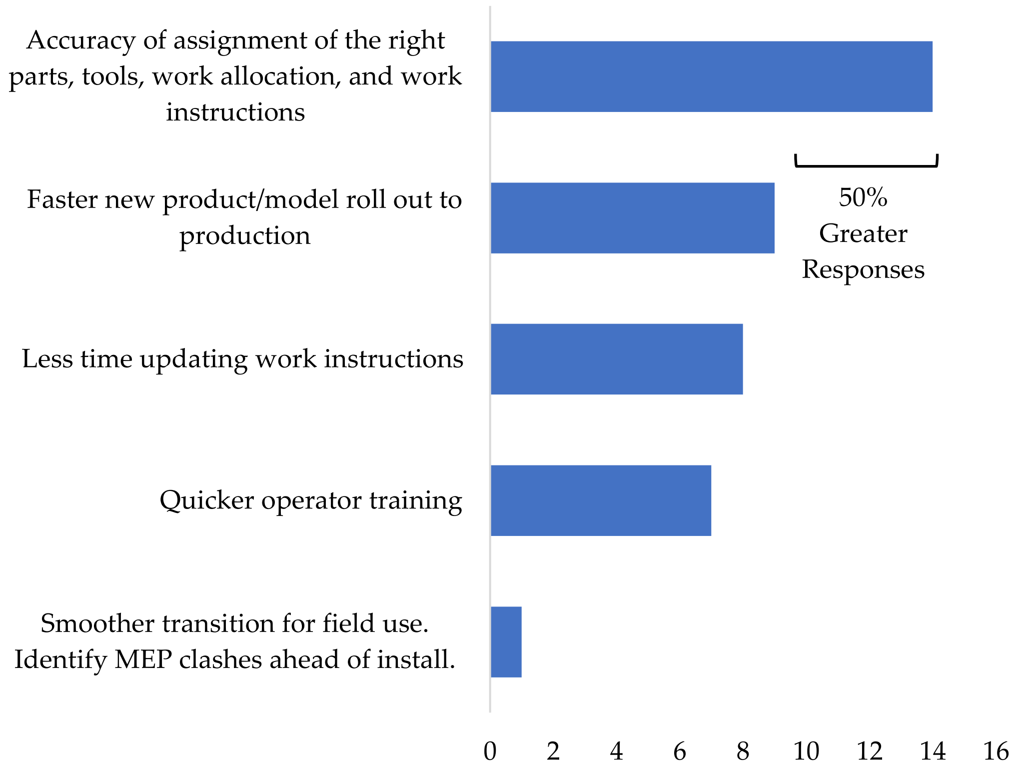

Figure 11. Value of 3D product model in the assembly process by response count.

Company Has Not Implemented the 3D Product Model in the Assembly Process but Plans to

Although the majority of the survey respondents had implemented the use of the 3D product model in the assembly planning and design or assembly shop floor execution processes, a small number of respondents had not. Of the five survey respondents that had not yet implemented the 3D product model in the assembly process, four said that their organizations planned to. The four respondents self-identified as somewhat knowledgeable (2), knowledge (1), and very knowledge (1) regarding their level of knowledge of 3D product model use in assembly processes. The individuals had varying titles, were from companies that ranged in size, and were from varying industries. As such, similar to the organizations that had already implemented the

3D product model in the assembly process, no one industry, company, or individuals' level within the company seemed to dominate or skew the data.

The plans to implement the 3D product model in the assembly process also varied but were amongst the less complex phases of the implementation of the 3D product model use in assembly process implementations, including using only screenshots of the 3D model and mapping the 3D product model to process activities. This makes sense, as the next logical step for a company that is not using the 3D product model in the assembly process is to move to a phase that allows them to capture value by doing so but does not require the investment/scope of a more complex implementation. The technology that respondents said their organizations planned to use to accomplish this was software that was developed in-house, which is what the majority of the respondents that had implemented the 3D product model in the assembly process had done, and the evaluation of Assembly Planner as the software platform.

Without the 3D product model in the assembly planning and design process, the respondents shared that their organizations are currently using Excel (2), physical mock-ups (1), and 3D model snapshots (1) to communicate the information today to the assembly planning and design team. The information contained in the 3D product model is currently being conveyed to the shop floor execution team through hard copy work instructions (3) and virtual work instructions that do not include the 3D product model (1). When the organizations do move from this current state to the future state of integrating the 3D product model in the assembly process, they expect to see value in areas ranging from less time updating work instructions (1); quicker operator training (1); accuracy of assignment of right parts, tools, work allocation, and work instructions (1); and faster new product/model roll out (1). One organization, who identified themselves as the smallest tier company available on the survey, shared that they believe implementing the 3D product model in the assembly process will save that organization $50,000 per year.

Company Has Not Implemented the 3D Product Model in the Assembly Process and Does Not Plan to

Only one respondent of the 28 responses analyzed said that they do not plan to implement the 3D product model in the assembly process. While this respondent shared that they are knowledgeable about the 3D product models use in the assembly process, that individual shared that they were unaware of technology solutions to integrate the 3D product model in the assembly process. It is the authors' aim that this paper will demonstrate such options to implement the 3D product model in the assembly process. Through the examples of how those organizations who have implemented the 3D product model in the assembly process transitioned to that state and the value that those companies have seen as a result, now other organizations such as the one noted here that are unaware of solutions to integrate 3D product models into the assembly process can see the value and direction through which they can do so.

Conclusions

The use of 3D product models beyond product design is gaining traction in industry. Companies are moving away from 2D drawings and paper-based work instructions to take advantage of the value that 3D product models offer beyond product design in not only the assembly planning and design process but also in shop floor execution. This survey disproved the research team's first hypothesis that the majority of companies would fall under the category of having not yet implemented the 3D product model in the assembly process but planned to do so, as most companies had already implemented the 3D product model in their assembly process.

While companies recognize that there is inherent value in applying the 3D product models beyond just product design, up to this point, much of that value is still described in ways that are very qualitative in nature. The research team failed to disprove the second hypothesis: that the value of using the 3D product model in the assembly process is expressed qualitatively and unknown quantitatively. Thus, future research focuses should include developing a more quantitative approach to the value companies can expect to gain when deploying 3D product models in the assembly planning and design process as well as in assembly shop floor execution.

In one application of the 3D product model in the assembly process, a large agricultural equipment manufacturer transitioned from using Microsoft Excel to reconcile engineering change orders to using the 3D product model in combination with Proplanner's Assembly Planner. In the original process using an Excel sheet, the company spent almost seven hours updating work instructions following an engineering change order. In the new process, the company could complete the same update, with the 3D product model included in the assembly process work instructions, in just over two hours. This resulted in a savings of over four and a half hours per engineering change order and with over 1500 engineering change orders processed each year that is greater than 6500 man-hours saved per year. By integrating the 3D product model into the assembly process, and automating that through Proplanner's Assembly Planner, the organization is able to save hundreds of thousands of dollars as a result.

In another application of the 3D product model in the assembly process, a large automotive manufacturer uses the 3D product model to verify assembly interferences before launching a product model change. The automotive manufacturer has a virtual assembly lab that allows them to complete such studies and check how a 3D product model change will work in the context of how it will integrate with tooling and the existing products already assembled onto the vehicle on the assembly line. The manager of the digital manufacturing group at this organization stated that the application of the 3D product model through the virtual assembly lab provides the company with a key competitive advantage over other automakers, where using the 3D product model in the assembly process saved millions of dollars in a new product launch.

Beyond these examples, the results shown in Figure 11 are substantial because they provide a framework through which industry and academia alike can start to develop a quantitative model for the value of the 3D product model in the assembly process. These five value areas can be used to determine the value of implementing the 3D product model on a given assembly line, which is then summed across assembly lines in a plant and across assembly plants within a company to get the enterprise value of implementing the 3D product model in the assembly process. The paper also demonstrates findings on which value drivers are more applicable to different size organizations and which value drivers are recognized the most in given industries. Then, via the survey results and the five value areas determined, this paper creates the building blocks for quantifying the value of the 3D product model in the assembly process in future research.

Author Contributions

C.K. and D.S. conceived the idea. C.K. formulated the problem, developed the survey, and worked with industry participants to collect and analyze the results. G.H. and D.S. provided guidance throughout the research and G.H. proofread the manuscript. All authors have read and agreed to this version of the manuscript.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data presented in this study are available as consolidated results in Section 3 of the manuscript. The individual response data are not publicly available due to the right of each survey participant to remain anonymous and only have the data shared as consolidated results.

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Conflicts of Interest

The authors declare no conflict of interest.

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CHAPTER 5. QUANTITATIVE MODEL FOR THE VALUE OF THE 3D PRODUCT MODEL USE IN PRODUCTION PROCESSES

Carl Kirpes[1], Dave Sly[1] and Guiping Hu [2]

[1] Industrial and Manufacturing Systems Engineering (IMSE), Iowa State University

[2] Department of Sustainability, Rochester Institute of Technology

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Abstract

Prior research has shown qualitatively that organizations can increase the value created in their production and assembly processes through the implementation of three-dimensional (3D) product models in those processes. This paper moves beyond qualitative value to develop and calibrate a quantitative model for the value of 3D product model use in production and assembly processes. The principal contributions of this research are development of the quantitative model and determination of the quantitative value of deploying the 3D product model in assembly and production processes; findings developed through interviews with industry experts in industrial and systems engineering to gather the model inputs, calculate the outputs, and then calibrate the model with those industry experts. These results are then compared against the qualitative value categories from prior research to determine the alignment in order and magnitude with the quantitative model results. This paper concludes with a recommendation of where both industry and academia focus future implementation efforts and research based upon the associated results demonstrated in both the qualitative and quantitative model on the value of 3D product model use in assembly and production processes.

Keywords

Assembly; process planning systems; concurrent engineering; automotive industry applications; manufacturing industry applications

Introduction

As the three-dimensional (3D) product model functionality has moved beyond its original purpose for use in the design phase to being able to be more broadly applied through production and business processes, the opportunity exists to develop a quantitative model for the value that the use of 3D product models brings to those processes. In review of the current literature, including journal papers, articles, and conference papers sourced using Compendex and Scopus databases, there is a great deal of research on 3D product models as well as significant research on assembly and production processes, but relatively little research has been performed on the overlap of the two and the corresponding value that has been created as a result of that combination [1]. This void in the body of literature could be in large part due to the unavailability of software that linked the 3D product model to the production and assembly processes [2,3]. As both research and industry has advanced in knowledge and expertise, this capability to link and deploy the engineering bill of materials and 3D product models to the manufacturing bill of materials and use of the 3D product model in the production processes has become more prevalent [4–16]. Academic research has been exploring the link between the value of the 3D product model and its use in assembly and production processes, however, thus far the results have been largely qualitative versus quantitative [1,17–24]. The objective of this research is to develop, propose, and demonstrate the results of a quantitative model for the deployment of the 3D product model in production and assembly processes.

The authors note that the 3D product model can have a large array of meanings from the virtual computer-aided design (CAD) model, to a digital mock-up, to a digital twin, or even a physical 3D model. As noted in the authors' prior work, the 3D product model application focused on in this paper is the value of bringing the virtual CAD model and digital 3D assembly mock-up to the assembly and production process beyond the engineering design. The example below was provided previously in the authors' published work, "*Value of the 3D Product Model Use in Assembly Processes: Process Planning, Design, and Shop Floor Execution*" and is included here again to give the reader a sense for an example of the type of application of the 3D product model the research is targeting [1].

"Figure 1 shows an assembly process where a fire truck is being built. Each octagon represents a station on the assembly line; some operations are completed by operators (the blue dots in the figure), and others are completed by robots. The operators have written work instructions which they use to know what parts to assemble and where to assemble those parts as different models and options of the fire truck progress down the assembly line. Figure 2 shows this same assembly line, but the written work instructions are replaced with 3D product models (virtual CAD models) of the part with visual assembly guidance. This is an example application of the 3D product model in the assembly process."

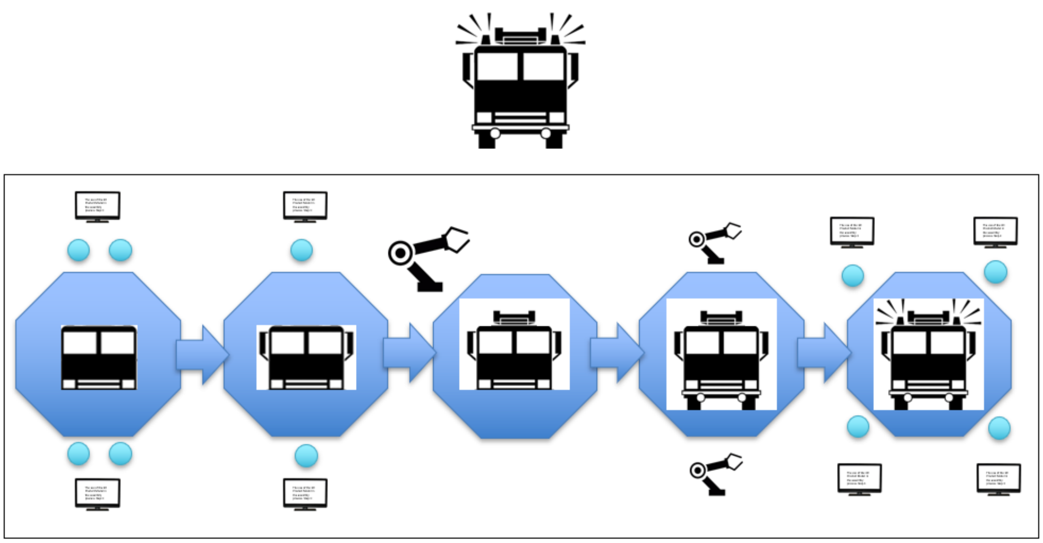

Figure 1. Assembly process using written work instructions [1].

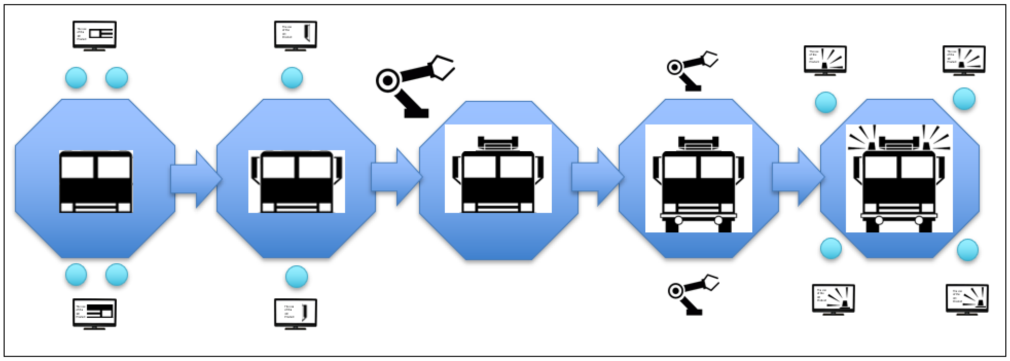

Figure 2. Assembly process deploying the 3D product model to the shop floor [1].

While deploying the 3D product model to the shop floor via visual work instructions is not the only way in which the 3D product model can be used in the production and assembly processes, it does demonstrate one example that creates value in some of the areas discussed in this paper, such as quicker operator training and less time updating work instructions. Other examples of the 3D product model applications in assembly and production processes include linking the 3D product model to the precedence diagram and checking for part interferences following engineering change orders, using the combination of the 3D product model and the precedence diagram to visualize how the assembly changes through the production process, and seeing the impact of changes made during the line balancing process represented by visual changes to 3D product model assembly [24]. The different ways in which the 3D product model is used in production and assembly processes creates different value, and the quantitative value models developed in this research aim to create a framework through which the value of using the 3D product model in the assembly process can be captured, across multiple application scenarios. This paper expands on the prior research which developed key areas where manufacturers see qualitative value in deploying the 3D product model in the production process and proposes a quantitative value model based on those results.

Materials and Methods

In this study, we develop a quantitative value model for the deployment of the 3D product model in production and assembly processes. This model is based off prior research in which the authors found that the areas of value in implementing the 3D product model in the production and assembly process are as follows (listed in order of greatest to least qualitative value):

1. Accuracy of assignment of the right parts, tools, work allocation, and work instructions;
2. Faster new product/model roll out to production;
3. Less time updating work instructions;
4. Quicker operator training;
5. Smoother transition for field use.

Thus, the quantitative value model has been developed around these key areas. Given the way in which the 3D product model is used to qualitatively create value in each of these areas is discussed in prior research, this article will not focus on how the 3D product model is used in those applications but rather focus on the determination of the quantitative value of deploying the 3D product model in these five value areas. The remainder of this section proposes a quantitative model for determining the value of 3D product model use in production and assembly processes.

Accuracy of Assignment of the Right Parts, Tools, Work Allocation, and Work Instructions Value Model

The accuracy of assignment of the right parts, tools, work allocation, and work instructions is the area that industry respondents indicated they found the most value in implementing the 3D product model in assembly processes, at a level over 50% greater than any other value area [1]. When the right parts, tools, work allocation, and work instructions are assigned to the right production line stations, it enables employees to reduce variation in the production time per station. Reduction in variability of production time per station leads to the capability to reduce the takt time, and thus generates a greater throughput on the production line. This concept is in alignment with Little's law which demonstrates that, all other things being equal, as variability in flow through a process is reduced, throughput rises [25]. Assuming a normal distribution in takt time variation by station, the model demonstrating this value is illustrated as follows:

M = Number of production/assembly lines in a manufacturing plant

m = A given production line in a manufacturing plant (1–M)

N_m = Number of stations on production line m

n = A given station on production line m (1–N)

$O_{m,n}$ = Number of operators at station n on production line m

o = A given operator at station n on production line m (1–O)

$T_{m,n}$ = Target takt time of station n on production line m

$\sigma_{T_{m,n}}$ = Standard deviation of takt time at station n on production line m

$\beta_{m,n}$ = Probability of $\hat{T}_{m,n} \leq T_m$

$Z_{\beta_{m,n}}$ = Z value of $\beta_{m,n}$

$\hat{T}_{m,n}$ = Actual takt time of station n on production line m for a given production instance

$$\hat{T}_{m,n} = T_{m,n} + Z_{\beta_{m,n}} \times \sigma_{T_{m,n}} \quad (1)$$

T_m = Takt time of production line m

$$T_m = \max_{n=1}^{N_m}\{Z_{\beta_{m,n}} \times \sigma_{T_{m,n}} + T_{m,n}\} \quad (2)$$

Thus, if the Target takt time of station n on production line m ($T_{m,n}$) and the desired probability of the actual takt time of station n on production line m being less than or equal to the takt time of production line m ($\beta_{m,n}$) remain the same across all stations on the production line m, then if the standard deviation can be decreased for each station n on line m ($\sigma_{T_{m,n}}$) the takt time of production line m can also be decreased (T_m). Note that this reduction in takt time of the production line m translates to a reduction in takt time of entire production process if the given production line is the bottleneck of the full manufacturing facility, otherwise speeding up the production line will not generate additional throughput through the production facility.

Presuming the production line is the bottleneck of the manufacturing process, here is what the model looks like in terms translating that takt time reduction to quantifiable dollars:

Ω_m = Total number of weeks production line m is in production per year

ω = A given week production line m is in production ($1–\Omega_m$)

δ_ω = Total number of days production line m is in production in week ω

$\bar{\delta}_m$ = Average number of days production line m is in production per week

$$\bar{\delta}_m = \sum_{\omega=1}^{\Omega_m} \delta_\omega / \Omega_m \tag{3}$$

D_m = Total number of days production line *m* is in production per year

$$D_m = \sum_{\omega=1}^{\Omega_m} \delta_\omega \text{ or } D_m = \bar{\delta}_m \times \Omega_m \tag{4}$$

d = A given day of the year of production line *m* production (1–D_m)

$H_{m,d}$ = Total time of production operation on production line *m* on day *d*

$\bar{H}_m$ = Average time of production operation on production line *m* per day

$$\bar{H}_m = \left(\sum_{d=1}^{D_m} H_{m,d}\right) / D_m \tag{5}$$

a = A given production produced on production line *m*

α_m = Average number of products produced on production line *m* per day

$$\alpha_m = \frac{\bar{H}_m}{T_m} \tag{6}$$

A_m = Products produced on production line *m* per year

$$A_m = \alpha_m \times D_m \quad (7)$$

$P_{m,a}$ = Profit generated by product a on line m

$\bar{P}_{A_M}$ = Average profit per product on production line m per year

$$\bar{P}_{A_m} = (\sum_{a=1}^{A_m} P_{m,a}) / A_m \quad (8)$$

$\bar{P}_{D_m}$ = Average profitability per day of production line m

$$\bar{P}_{D_m} = \alpha_m \times \bar{P}_{A_M} \quad (9)$$

P_{Y_m} = Profitability per year per production line m

$$P_{Y_m} = \bar{P}_{D_m} \times D_m \ or\ \bar{P}_{A_m} \times A_m \quad (10)$$

$P_{Without3D,\, m}$ = Profitability per year for production line m (P_{Y_m}) prior to 3D product model implementation in production processes

$P_{With3D,\, m}$ = Profitability to per year for production line m (P_{Y_m}) after 3D product model implementation in production processes

P_{T_m} = Incremental profitability via reduction in Takt Time

$$P_{T_m} = P_{\mathrm{Without3}D,m} - P_{\mathrm{With3}D,m} \tag{11}$$

Faster New Product/Model Roll Out to Production

A number of industry respondents, including a large agriculture equipment manufacture and a large automotive manufacturer indicated that the area which they have found a great deal of value in implementing the 3D product model is in faster new product/model roll out. This concept is in alignment with Goldratt's Theory of Constraints, where elevating the performance/uptime of the constraint (the production/assembly process) increases the throughput for the system [26]. The model for the value created through the time saved in production start-up by implementing the 3D product model in the production process is demonstrated below:

U_m = Increased uptime following new product or model roll out for production line *m*

E = Number of new product or model roll outs per year

P_{U_m} = Incremental profitability due to increased uptime on production line *m*

$$P_{U_m} = U_m \times E \times \bar{P}_{D_m} \tag{12}$$

Less Time Updating Work Instructions

When an engineering change order (ECO) is released, it creates an update to the product model and often requires an update to the associated work instruction for the production station effected by that ECO. When the 3D product model is linked to the production and assembly precedence diagram, a change to either the 3D product model or the precedence generates an update to the visual work instructions automatically when the ECO is processed. This then saves the engineer time they would have spent manually updating written work instructions. The time manually updating the work instruction can be classified as non-value-added time according to the principles of Frank and Lillian Gilbreth [27]. Reducing this non-value-added time is one way to drive value in a system. The model for the value created through less time updating work instructions by using 3D product model production process software is demonstrated as:

$W_{m,n,k}$ = Time to update work instruction k for station n on production line m

$K_{m,n}$ = Number of work instructions updated per year per station n on production line m

k = A given work instruction update on station n on production line m (1–$K_{m,n}$)

K_m = Number of work instructions updated per year on production line m

$$K_m = \sum_{n=1}^{N} K_{m,n} \tag{13}$$

$\bar{W}_m$ = Average time to update a work instruction for production line m

$$\bar{W}_m = \left(\sum_{n=1}^{N} \frac{\sum_{k=1}^{K_{m,n}} W_{m,n,k}}{K_{m,n}}\right) / N \tag{14}$$

$\bar{\Gamma}$ = Average cost of labor per hour to update work instructions

C_m = Cost to update work instructions on production line m

$$C_m = \bar{W}_m \times K_m \times \bar{\Gamma} \tag{15}$$

$C_{\text{Without}3D,m}$ = Cost to update work instructions (C_m) for production line m prior to 3D product model implementation in production processes

$C_{\text{With}3D,m}$ = Cost to update work instructions (C_m) for production line m after 3D product model implementation in production processes

P_{W_m} = Incremental profitability via reduction in time to update work instructions

$$P_{W_m} = C_{\text{Without}3D,m} - C_{\text{With}3D,m} \tag{16}$$

Quicker Operator Training

The fourth of five categories, as seen in the first paragraph of the Materials and Methods section, in which industry respondents indicated they created value by implementing the use of the 3D product model in the production process is in quicker operator training. By having the 3D product model use in the production process, employees that need to be trained on a new or updated production process can see the 3D model of the product and gain a visual representation for the objective to be achieved, increasing the speed at which they learn to perform the operation within the target takt time for station n on production line m ($T_{m,n}$). Here we apply the learning curve theory [28] to model the value that the 3D product model use in the production process creates via quicker operator training:

$\Psi_{m,n,o,1}$ = Time to produce the 1st unit by operator o at station n on production line m

$L_{m,n,o}$ = Learning curve rate for operator o at station n on production line m

δ = Production unit number

b = Learning curve factor

$$b = \frac{\ln\left(L_{m,n,o}\right)}{\ln(2)} \tag{17}$$

$\Psi_{m,n,o,\delta}$ = Amount of time to produce unit δ by operator o at station n on production line m

$$\Psi_{m,n,o,\delta} = \Psi_{m,n,o,1} \times \delta^{b} \tag{18}$$

$\Psi_{m,o}$ = Time operator o spends training at station n on production line m

$$\Psi_{m,n,o} = \sum_{\delta=1}^{\Psi_{m,n,o,\delta} \leq T_{m.n}} \Psi_{m,n,o,\delta} \tag{19}$$

$x_{m,n,o}$ = Number of required trainings per operator o at station n on production line m per year (due to turnover, minor work instruction/product model updates, etc.)

$X_{m,n}$ = Number of employees trainings at station n on production line m per year

$$X_{m,n} = O_{m,n} \times E + \sum_{o=1}^{O_{m,n}} x_{m,n,o} \tag{20}$$

$\Psi_{m,}$ = Total time spent training on station n on production line m

$$\Psi_{m,n} = \sum_{o=1}^{X_{m.n}} \Psi_{m,n,o} \tag{21}$$

$\gamma_{m,n,o}$ = Hours worked by operator *o* at station *n* on production line *m*

$\zeta_{m,n,o}$ = Cost of labor per hour for operator *o* at station *n* on production line *m*

$\zeta_{m,}$ = Average cost of labor per hour for operators at station *n* on production line *m*

$$\bar{\zeta}_{m,n} = (\sum_{o=1}^{O_{m.n}} \zeta_{m,n,o} \times \gamma_{m,n,o}) / \sum_{o=1}^{O_{m.n}} \gamma_{m,n,o} \tag{22}$$

Φ_m = Cost of training for production line *m*

$$\Phi_m = \sum_{n=1}^{N_m} \bar{\zeta}_{m,n} \times \Psi_{m,n} \tag{23}$$

$\Phi_{\mathrm{Without3D},m}$ = Cost of training for production line *m* (Φ_m) prior to 3D product model implementation in production processes

$\Phi_{\mathrm{With3D},m}$ = Cost of training for production line *m* (Φ_m) after 3D product model implementation in production processes

P_{Φ_m} = Incremental profitability via reduction in time to update work instructions

$$P_{\Phi_m} = \Phi_{\mathrm{Without}3D,m} - \Phi_{\mathrm{With}3D,m} \qquad (24)$$

Smoother Transition to Field Use by Identifying Clashes Ahead of Install

In another application of the 3D product model in the production process, a large automotive manufacturer uses the 3D product model to verify production and assembly interferences before launching a product model change. The automotive manufacturer has a virtual assembly lab that allows them to complete such studies and check how a 3D product model change will work in the context of how it will integrate with tooling and the existing products already assembled onto the vehicle on the production line. The manager of the digital manufacturing group at this organization stated that the application of the 3D product model through the virtual production lab provides the company with a key competitive advantage over other automakers. Such an improvement can lead to the reliability of the work being performed at the production and assembly stations as a result of a product and work station design that was developed with ease of manufacturing and assembly as a core intent which was enabled by the implementation of the 3D product model in the production planning and design processes. Taiichi Ohno in his work on the Toyota Production System describes seven wastes, one of which is defects [29]. By using the 3D product model in the production and assembly process to reduce these defects, waste in the system is removed and thus more value is generated. The model for the quantitative dollar value of this increase in reliability creates, as a result of the design for assembly enabled by using the 3D product model in the production planning and design process, is as follows:

$R_{m,n}$ = Reliability of station n on production line m

R_m = Reliability of production line m

$$R_m = R_{m,1} \times R_{m,2} \times R_{m,3} \times \ldots R_{m,N} \tag{25}$$

Note that if the reliability of all stations on production line *m* are the same then

$$R_m = \left(R_{m,N}\right)^\wedge N \tag{26}$$

η = Number of assembled units reworked

$$\eta = (1 - R_m) \times A_m \tag{27}$$

$\xi_{m,a}$ = Cost of rework for product *a* on production line *m*

$\bar{\xi}_m$ = Average cost of rework for a unit that requires rework on production line *m*

$$\bar{\xi}_m = \left(\sum_{a=1}^{\eta} \xi_{m,a}\right)/\eta \tag{28}$$

Q_m = Cost of rework on production line *m*

$$Q_m = \bar{\xi}_m \times \eta \tag{29}$$

$Q_{\text{Without}3D,m}$ = Cost of rework for production line *m* (Q_m) prior to 3D product model implementation in production processes

$Q_{\text{With}3D,m}$ = Cost of rework for production line m (Q_m) after 3D product model implementation in production processes

P_{Q_m} = Incremental profitability via reduction rework

$$P_{Q_m} = Q_{\text{Without}3D,m} - Q_{\text{With}3D,m} \quad (30)$$

Total Value of Implementing the 3D Product Model in Production and Assembly Processes

The industry respondents who have implemented the 3D product model in their production and assembly processes indicated five categories in which they were gaining value through that implementation. The total quantitative value gained on a given production line by implementing the 3D product model into a production process can then be shown as:

V_m = total value gained for production line m by using 3D product models in the production process:

$$V_m = P_{T_m} + P_{U_m} + P_{W_m} + P_{\Phi_m} + P_{Q_m} \quad (31)$$

These equations that the research team developed and applied for determining the quantitative value of implementing the 3D product model in the production and assembly processes were then translated into a graphical user interface that allows for industry and academia alike to input the key independent variables and calculates the results that implementing the 3D product model will create. This user interface is shown in Figure 3.

The research team used the quantitative model equations outlined in the Materials and Methods section of this paper to develop the associated graphical user interface tool (shown in Figure 3) to simplify the translations of the data inputs to the quantitative value outputs. The research team then used the graphical user interface in a series of interviews with industry experts engaged in industrial and systems engineering leadership in for-profit manufacturing enterprises. The cells in the graphical user interface in Figure 3 that are gray are generated based on numerical calculations developed in this paper. The cells that are blank and highlighted in color are where inputs that are gathered through interviews with industry experts are entered. The purpose of the interviews was for the companies to provide the inputs to the model, which would then generate the representative output of the value that deploying the 3D product model in the production process would/did create. These results were then calibrated against the industry experts understanding of the value the 3D product model created or would create when deployed to the production and assembly processes. Note that the nature of the organizations surveyed are such that all other variables were not able to be held constant when deploying the 3D product model to the production and assembly process. The objective was to complete applied research in which the quantitative model was utilized in a production setting. As indicated in the conclusion, further research in this area can be conducted that further isolates variables that impact value generated for an organization so that additional certainty can be gained around the correlation of the implementation of the 3D product model in assembly and production processes and the associated financial benefit the company realizes.

Prior to analyzing the survey results, the research team's hypothesis was that the quantitative model would show the greatest value generation in each identified area (accuracy of assignment of the right parts, tools, work allocation, and work instructions; faster new product/model roll out to production; less time updating work instructions; quicker operator training; smoother transition for field use) to a similar magnitude as the qualitative results had showed in the prior research. Thus, as an example, accuracy of assignment of the right parts, tools, work allocation, and work instructions would show value that was 50% greater than the quantitative value generated in any of the four other value areas.

Value Model	Description	Variable	Example w/o 3D	Example w/3D
Assignment of the Right Parts, Tools, Work Allocation, and Work Instructions	Number of Production Lines in Manufacturing Plant	M		0
	Number of Production stations on production line m	N_m		0
	Number of operators at station n on production line m	$O_{m,n}$		0
	Target Takt time of station n on production line m (seconds)	$T_{m,n}$		0
	Standard deviation of Takt time at station *n* on production line *m* (seconds)	$\sigma_{T_{m,n}}$		
	Probability of $\hat{T}_{m,n} \leq T_m$	$\beta_{m,n}$		0.00%
	Z value of $\beta_{m,n}$	$Z_{\beta_{m,n}}$		0
	Actual Takt Time of station n on production line m for a given production instance (seconds)	$\hat{T}_{m,n}$	-	-
	Takt time of production line *m* (seconds)	T_m	-	-
	Total number of weeks production line *m* is in production per year	Ω_m		0
	Average number of days production line m is in production per week	$\bar{\delta}_m$		0
	Total number of days production line *m* is in production per year	D_m	-	-
	Average time of production operation on production line m per day (hours)	$\bar{H}_m$		0
	Average number of products produced on production line m per day	α_m	-	-
	Products produced on production line m per year	A_m	-	-
	Average Profit per production on line m per year	$\bar{P}_{A_M}$		$ -
	Average Profitability per day of production line m	$\bar{P}_{D_m}$	$ -	$ -
	Profitability per year per production line m	P_{Y_m}	$ -	$ -
	Is Production the Bottleneck of the Manufacturing Facility? (Yes or No)			0
	Incremental Profitability via reduction in Takt Time	P_{T_m}	$0	
Faster New Product/Model Roll Out	Increased uptime following new product or model roll out for production line m (days)	U_m		
	Number of new product or model roll outs per year	E		0
	Incremental Profitability due to increased uptime on production line *m*	P_{U_m}	$0	
Less Time Updating Work Instructions	Number of Work Instructions updated per year per station *n* on production line *m*	$K_{m,n}$		-
	Number of Work Instructions updated per year on production line *m*	K_m	-	-
	Average time to update a work instruction for production line *m* (minutes)	$\bar{W}_m$		
	Average Cost of labor per hour to update work instructions (dollars per hour)	$\bar{\Gamma}$		$ -
	Cost to update work instructions on production line *m*	C_m	$ -	$ -
	Incremental Profitability via reduction in time to update Work Instructions	P_{W_m}	$0	
Quicker Operator Training	Time to produce the 1st unit by for operator *o* at station *n* on production line *m* (seconds)	$\Psi_{m,n,o,1}$		
	Learning Curve Rate for Operator *o* at station *n* on production line *n*	$L_{m,n,o}$		
	Learning curve factor	b	0.000	0.000
	Time operator *o* spends training at station *n* on production line *m* (hours)	$\Psi_{m,n,o}$	-	-
	Number of required trainings per operator *o* at station *n* on production line *m* per year (due to turnover, work instruction/product model updates)	$x_{m,n,o}$		-
	Number of employees trainings at station *n* on production line *m* per year	$X_{m,n}$	-	-
	Total Time spent training on station *m* on production line *n* (hours)	$\Psi_{m,n}$	-	-
	Average cost of labor per hour for operators at station *n* on production line *m* (dollars per hour)	$\bar{\zeta}_{m,n}$		$ -
	Cost of training for production line *m*	Φ_m	$ -	$ -
	Incremental Profitability via reduction in time to update Work Instructions	P_{Φ_m}	$0	
Smoother Transition to Field Use. Identify MEP Clashes ahead of Install	Reliability (First Line Capability) of station *n* on production line *m*	$R_{m,n}$		
	Reliability of production line *m*	R_m	0.0%	0.0%
	Number of assembled units reworked (per year)	η	-	-
	Average cost of rework for a unit that requires rework on production line *m*	$\bar{\xi}_m$		$ -
	Cost of rework on production line *m* (per year)	Q_m	$ -	$ -
	Incremental Profitability via reduction rework	P_{Q_m}	$0	
Total Value	Total Value Before Costs (per year)	V_m	**$0**	
	Percent Increase in Profitability		0.0%	

Figure 3. The 3D Product Model Value in Production Process—Quantitative Model Input Sheet.

Results

Accuracy of Assignment of the Right Parts, Tools, Work Allocation, and Work Instructions Value Model

An aggregation of data collected from interviews with industry experts in industrial and systems engineering leadership roles will be used to demonstrate the application of the model developed in the Materials and Methods section of this paper. One large automotive manufacture makes vehicles on a production line with a production line takt time of 60 s (T_m). Although each station along a production line will have its own inherent variability, in this aggregate analysis all production stations have the same target station takt time of 54 s ($T_{m,n}$) with a standard deviation of 3 s ($\sigma_{T_{m,n}}$). This results in a probability that each station will be able to keep up with the production line takt time of 60 s 97.7% of the time. Now, if that automotive manufacturer introduces the 3D product model into the production process, the company can reduce the variability of the time to complete an operation at a station given all of the right parts, tools, work allocation, and work instructions have been implemented. By reducing the standard deviation from 3 to 2 s as a result, reducing the standard deviation by 1 s while retaining the 54 s average takt time and retaining the 97.7% probability of completing the task within the production line task time, the takt time can be reduced by 2 s to approximately 58 s. This is a 3.3% reduction in production line takt time, allowing the company to produce approximately 3.3% more products per year (if production is the bottleneck in the overall manufacturing facility).

In this aggregate example, prior to the 3D product model use in the production process, the average takt time of the line (T_m) is 60 s, the production line operates 24 h per day ($\overline{H}_m$), so the assemblies produced on the line per day (α_m) is 1440. The automotive manufacturer makes an average profit ($\overline{P}_{A_M}$) on cars of approximately USD 5000 per vehicle (note that profit on trucks and sports utility vehicles [SUVs] is significantly more at closer to USD 20,000–25,000 per vehicle, and thus the value demonstrated throughout this paper would be much greater in dollar volume if applied to an SUV or truck production line). This results in an average daily profit ($\bar{P}_{D_m}$) of USD 7.2 million. This automotive plant runs their production lines 5 days a week ($\bar{\delta}_m$) for 50 weeks per year (Ω_m). The production line is down for maintenance work on weekends and over the fourth of July and Christmas holidays for a week each, resulting in 250 days of operation per year (D_m). This generates a yearly profitability for that production line (P_{Y_m}) of USD 1.8 billion. Now when the 3D product model is introduced in the production process and reduces the standard deviation of the takt time at the stations, the products produced on the line per day (α_m) increase to 1490 based on the 58 s takt time, or 50 more assembled units per day. This increase in production generates a daily profit ($\bar{P}_{D_m}$) of USD 7.45 M, or an increase of USD 0.25 million per day. The yearly profit (P_{Y_m}) increases as a result, to USD 1.86 billion, or an increase of approximately USD 62 million per year for that production line (P_{T_m}). Note that if multiple production lines were improved via reduced variation from the implementation of the 3D product model in the production process, the value could be summed across these multiple production lines to capture the profitability benefit per year for a given plant. The profitability increases across all plants could then be summed to capture the total value for the increase in value generated by the implementation of the 3D product model in the production process. This aggregation within a production plant and an entire organization is a topic for future research, as other interaction effects and lurking variables may exist when evaluating the system at this level.

Faster New Product/Model Roll Out to Production

In order to have cohesiveness between the varying sections of this paper, the average profitability per day ($\bar{P}_{D_m}$) calculated in the prior section, at the 60 s takt time, will be used throughout the paper. Note, that although the prior section demonstrated a decrease in takt time by implementing the 3D product model in the production process and such an effect would increase the incremental profitability demonstrated here, that is not being taken into account in this section. Such effects are called interaction factors between variables and can be considered in future research.

By having the 3D product model used in production processes, an automotive manufacturer was able to reduce the time before the production line was fully operational after introducing a new product/model from what had traditionally been 4 weeks of equivalent lost production time down to 2 weeks of equivalent lost production time, ultimately increasing the uptime of the line by 10 days. With the increase in uptime following the new product/model roll out (U_m) of 10 days, and with 0.2 new product/model roll outs per year (E) (or in other words, a new product/model roll out once every five years) then the incremental profitability on the line is USD 14.4 million per year (P_{U_m}). Using the 3D product model in the production process to generate faster new product/model roll outs results in an increase in profitability of 0.8%.

Less Time Updating Work Instructions

In another application of the 3D product model in the production process, an agricultural equipment manufacturer transitioned from using Microsoft Excel to reconcile engineering change orders with work instructions to using the 3D product model in combination with Proplanner's Assembly Planner. In the original process using an Excel sheet, the company spent almost seven hours updating work instructions ($\overline{W}_m$) following an engineering change order. In the new process, the company could complete the same update, with the 3D product model included in the production process work instructions, in just over two hours. This resulted in a savings of over four and a half hours per engineering change order and with around 245 engineering change orders per line processed each year (K_m) that is over 1000 man-hours saved per year per production line. The company has industrial engineers with an average fully loaded cost of USD 60 per labor hour ($\bar{\Gamma}$) updating the work instructions manually. By integrating the 3D product model into the production process, and automating that through Proplanner's Assembly Planner, the organization is able to save USD 60,000 per year per line (P_{W_m}) as a result, reducing the cost associated with updating wok instructions by over 67%.

Quicker Operator Training

In an automotive manufacturer, the target takt time at station *n* on production line *m* ($T_{m,n}$) is 54 s, and a new operator takes three times as long, i.e., 162 s, to complete the new production task on their first attempt ($\Psi_{m,n,o,1}$). Prior to the implementation of 3D product model software in the shop floor training, the learning rate for this operator ($L_{m,n,o}$) is 86%. This means that each time the operator performs the task, on average, the operator will perform the same task 14% faster than the time before. This then creates a learning curve through which we can model the total time training before the operator reaches a time ($\Psi_{m,n,o,\delta}$) that is as good as or better than the target takt time for that station *n* on production line *m* ($T_{m,n}$). The total time training between the initial attempt and when the target takt time is reached is the total time that operator spends training ($\Psi_{m,n,o}$), which using the initial production time, learning curve percent, and target takt time above equates to three hours of training per operator. To capture the total time spent training at station *n* on production line *m* the sum of all operators who were trained on the update at station *n* on production line *m* is calculated ($\Psi_{m,n}$). For this manufacturer, on average there are two operators per station per shift, two shifts, 350 stations per production line, and one production line. To translate the training time to quantitative cost of training dollars for production line m (Φ_m) the average cost of operators at station *n* on production line *m* ($\overline{\zeta_{m,n}}$), a good approximation is USD 30/h fully loaded (including burden rate) multiplied by the total time spent training at station *n* on production line *m* across all stations on line *m*. This results in a training cost (Φ_m) of close to USD 400,000 per year, under the approximation that all operators have the same learning curve rate of 86% and their first attempt at the new production process was three times longer than the target takt time. However, the implementation of the 3D product model in the production process creates an opportunity for operators to understand and visualize the production process before performing it. This knowledge enables the operator to reduce the time required in their first attempt to conduct the production process to two times the target tact time while the learning curve rate remains the same at 86% (meaning the operator still performs the task 14% better each time). This reduces the operators total training time to 0.5 h, and the operator is able to achieve the target takt time in 25 training attempts, as opposed to 155 prior to the implementation of the 3D product model in the production process. This significantly reduces the training cost for the operators to learn the new production processes as the product model changes, saving hundreds of thousands of dollars per year (P_{Φ_m}) and reducing training costs by 84% while still maintaining the operators' ability to meet the target takt time.

Smoother Transition to Field Use

In alignment with the prior operator training example, there are 350 stations per production line (N_m). Prior to implementing the 3D product model, the automotive manufacturer discussed in this example has a reliability of each station on a given line ($R_{m,n}$) producing a quality product of 99.97% per station. This results in an overall reliability of the production line (R_m) producing quality products 90% of the time, meaning 10% of the products need to be re-worked. The average price to re-work a product ($\bar{\xi}_m$) is USD 60 (two operator labor hours) on this production line, which with the production throughput and profitability rates noted earlier in the paper, result in a rework cost of over USD 2 million per year on one line (Q_m). With the implementation of the 3D product model in the production planning and design process, the product is designed such that it improves the ease of manufacturability and removes possibilities for incorrect assembly (poka-yoke). This increases the probability of each station on the line producing quality products at their station by two hundredths of a percent to 99.99%. The result is rework costs reducing to less than USD 0.74 million per year on that production line, saving the company over USD 1.4 million each year in rework on that assembly line (P_{Q_m}) via a 65% decrease in re-work costs.

Total Value of Implementing the 3D Product Model in Production and Assembly Processes

Each value area noted above provides an example applied to the quantitative model that can be used by companies and researchers alike to better understand the value that 3D product models can create when used in production processes. With the combination of the value creation across the demonstrated value areas, the total value generated is over USD 78 million in profit per production line (V_m), an increase of over 4.3% in profitability in this model composed of aggregated data. The resulting data shown in the graphical user interface in Figure 4 are an aggregate of the information from interviews with industry experts discussed throughout the Results section.

While this research provides a guideline on the quantitative value that the 3D product model can bring to organizations that deploy it to the production and assembly processes, the authors recognize that the results can vary by company. Given this, the authors completed a tornado diagram to demonstrate percent profitability increases as high and low values using data compiled across the six research companies, as show in Figure 5. This serves as a sensitivity analysis of the range of values any one company may anticipate in deploying the 3D product model to the production and assembly processes.

Value Model	Description	Variable	Example w/o 3D	Example w/3D
Assignment of the Right Parts, Tools, Work Allocation, and Work Instructions	Number of Production Lines in Manufacturing Plant	M	1	1
	Number of Production stations on production line m	N_m	350	350
	Number of operators at station n on production line m	$O_{m,n}$	4	4
	Target Takt time of station n on production line m (seconds)	$T_{m,n}$	54	54
	Standard deviation of Takt time at station *n* on production line *m* (seconds)	$\sigma_{T_{m,n}}$	3	2
	Probability of $\hat{T}_{m,n} \leq T_m$	$\beta_{m,n}$	97.70%	97.70%
	Z value of $\beta_{m,n}$	$z_{\beta_{m,n}}$	2	2
	Actual Takt Time of station n on production line m for a given production instance (seconds)	$\hat{T}_{m,n}$	60	58
	Takt time of production line *m* (seconds)	T_m	60	58
	Total number of weeks production line *m* is in production per year	Ω_m	50	50
	Average number of days production line m is in production per week	$\bar{\delta}_m$	5	5
	Total number of days production line *m* is in production per year	D_m	250	250
	Average time of production operation on production line m per day (hours)	$\bar{H}_m$	24	24
	Average number of products produced on production line m per day	α_m	1,440	1,490
	Products produced on production line m per year	A_m	360,000	372,414
	Average Profit per production on line m per year	$\bar{P}_{A_M}$	$ 5,000	$ 5,000
	Average Profitability per day of production line m	$\bar{P}_{D_m}$	$ 7,200,000	$ 7,448,276
	Profitability per year per production line m	P_{Y_m}	$ 1,800,000,000	$ 1,862,068,966
	Is Production the Bottleneck of the Manufacturing Facility? (Yes or No)		Yes	Yes
	Incremental Profitability via reduction in Takt Time	P_{T_m}	$62,068,966	
Faster New Product/Model Roll Out	Increased uptime following new product or model roll out for production line m (days)	U_m	0	10
	Number of new product or model roll outs per year	E	0.2	0.2
	Incremental Profitability due to increased uptime on production line *m*	P_{U_m}	$14,400,000	
Less Time Updating Work Instructions	Number of Work Instructions updated per year per station *n* on production line *m*	$K_{m,n}$	0.7	0.7
	Number of Work Instructions updated per year on production line *m*	K_m	245	245
	Average time to update a work instruction for production line *m* (minutes)	$\bar{W}_m$	415	135
	Average Cost of labor per hour to update work instructions (dollars per hour)	$\bar{\Gamma}$	$ 60	$ 60
	Cost to update work instructions on production line *m*	C_m	$ 101,675	$ 33,075
	Incremental Profitability via reduction in time to update Work Instructions	P_{W_m}	$68,600	
Quicker Operator Training	Time to produce the 1st unit by for operator *o* at station *n* on production line *m* (seconds)	$\Psi_{m,n,o,1}$	162	108
	Learning Curve Rate for Operator *o* at station *n* on production line *n*	$L_{m,n,o}$	86%	86%
	Learning curve factor	b	-0.218	-0.218
	Time operator *o* spends training at station *n* on production line *m* (hours)	$\Psi_{m,n,o}$	3.0	0.5
	Number of required trainings per operator *o* at station *n* on production line *m* per year (due to turnover, work instruction/product model updates)	$x_{m,n,o}$	3	3
	Number of employees trainings at station *n* on production line *m* per year	$X_{m,n}$	12.8	12.8
	Total Time spent training on station *m* on production line *n* (hours)	$\Psi_{m,n}$	37.9	5.9
	Average cost of labor per hour for operators at station *n* on production line *m* (dollars per hour)	$\bar{\zeta}_{m,n}$	$ 30	$ 30
	Cost of training for production line *m*	Φ_m	$ 398,288	$ 61,883
	Incremental Profitability via reduction in time to update Work Instructions	P_{Φ_m}	$336,405	
Smoother Transition to Field Use. Identify MEP Clashes ahead of Install	Reliability (First Line Capability) of station *n* on production line *m*	$R_{m,n}$	99.97%	99.99%
	Reliability of production line *m*	R_m	90.0%	96.6%
	Number of assembled units reworked (per year)	η	35,888.28	12,383
	Average cost of rework for a unit that requires rework on production line *m*	$\bar{\xi}_m$	$ 60	$ 60
	Cost of rework on production line *m* (per year)	Q_m	$ 2,153,297	$ 742,960
	Incremental Profitability via reduction rework	P_{Q_m}	$1,410,337	
Total Value	Total Value Before Costs (per year)	V_m	**$78,284,308**	
	Percent Increase in Profitability		4.3%	

Figure 4. The 3D Product Model Value in Production Process–Quantitative Model Input Sheet with Values.

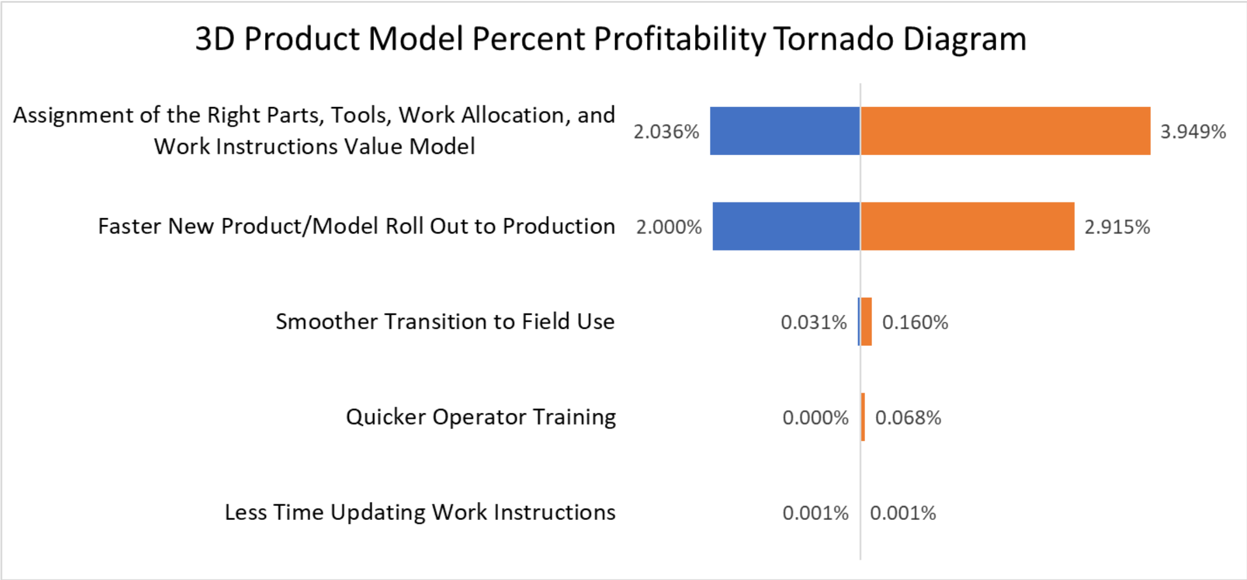

Figure 5: Tornado Diagram of Percent Profitability Increase by Value Area

The low end of all value areas in Figure 5 is zero, which is because the costs associated with the implementation of the 3D product model to the production and assembly process were not considered in this paper. As such, the worst any one category could do was deliver no results. The tornado diagram also demonstrates that the potential for value capture in less time updating work instructions and quicker operator training is minuscule compared to the other three categories. However, the authors included these categories as companies often found these two value areas the easiest to quantify and predict what the value would be before deploying the 3D product model to the production and assembly process. As a result, companies were using these two value areas to justify the deployment of the 3D product model in the production and assembly processes, getting the project approved knowing there were likely larger benefits in the other three areas but not being able to predict what that value would be and thus unable to use the value from those other areas in a project justification.

The data gathered in this study can also be evaluated between companies versus aggregated across companies as show in Figure 4. Figure 6 demonstrates a breakdown of the value by company, using three of the companies from this study as a comparison. The data is provided as a percentage increase in profitability to provide anonymity to the companies and no company names are given. Figure 6 shows that while the value in any one value area may be different between companies, the magnitudes of value within a company are often similar where (1) Assignment of the right parts, tools, work allocation and work instructions and (2) faster new product/model roll out to production are often the greatest value areas that companies realize. These results also provide a level of confidence in the model in that the results can translate across companies and industries.

3D Product Model Value Categories	Increase in Profitability		
	Company A	Company B	Company C
Assignment of the Right Parts, Tools, Work Allocation, and work instructions Value Model	3.44%	2.04%	3.95%
Faster new Product/Model Roll Out to production	2.00%	2.40%	2.92%
Less Time Updating Work Instructions	0.00%	0.00%	0.00%
Quicker Operator Training	0.07%	0.01%	0.00%
Smoother Transition to Field Use. Identify MEP Clashes ahead of Install	0.08%	0.16%	0.03%
Total Value	5.59%	4.61%	6.90%

Figure 6: 3D Product Model Value Categories Comparison across companies

Future research can be undertaken to better understand the interaction effects between these areas of value, seeing if perhaps some value is being dual counted between areas, or if some additional value is generated by the interaction of varying areas of value which is greater than the sum of the individual value calculations. In addition, we note that the value described here is incremental profit without accounting for the costs of implementing the 3D product model software in production processes. In further research, these implementation and maintenance costs of the software that enables the use of the 3D product model in production processes can be described and articulated in terms of a cost benefit analysis. This research also does not take into account any tradeoffs that might occur in terms of loss of value when replacing legacy processes with the implementation of the 3D product model in production and assembly processes, and thus there is an opportunity for future research in that arena. In addition, the data extracted from the examples included above are the result of a sample size of six companies, so further research can be performed to incrementally validate the quantitative models developed in this research.

Discussion

Much of the prior research undertaken on the value of the 3D product model in assembly and production processes has either been qualitative in nature or limited to an individual company in scope, whereas this research aims to generate a quantitative model and quantitative value for the deployment of the 3D product model in production and assembly processes. The example below was provided previously in the authors' published work, "*Value of the 3D Product Model Use in Assembly Processes: Process Planning, Design, and Shop Floor Execution*," and is included here to give the reader a sense for how this research compares to existing published research [1].

"The plot of the relative densities of "3D" to "assembly" [average word count per page], where "value creation" is the size of each bubble, is shown in Figure 7, where each different colored bubble represents a different journal paper, article, or conference paper. Figure 7 demonstrates that while there was a lot of research published on 3D product models, and an equivalent amount published on assembly processes, less literature had been published on the use of 3D product models in assembly. This was especially evident in the lack of data points in the upper right corner of Figure 7 and the fact that of those papers that do have a high density of "3D" and "assembly", there is still a gap in the literature in terms of the value that the use of 3D product models creates in assembly processes."

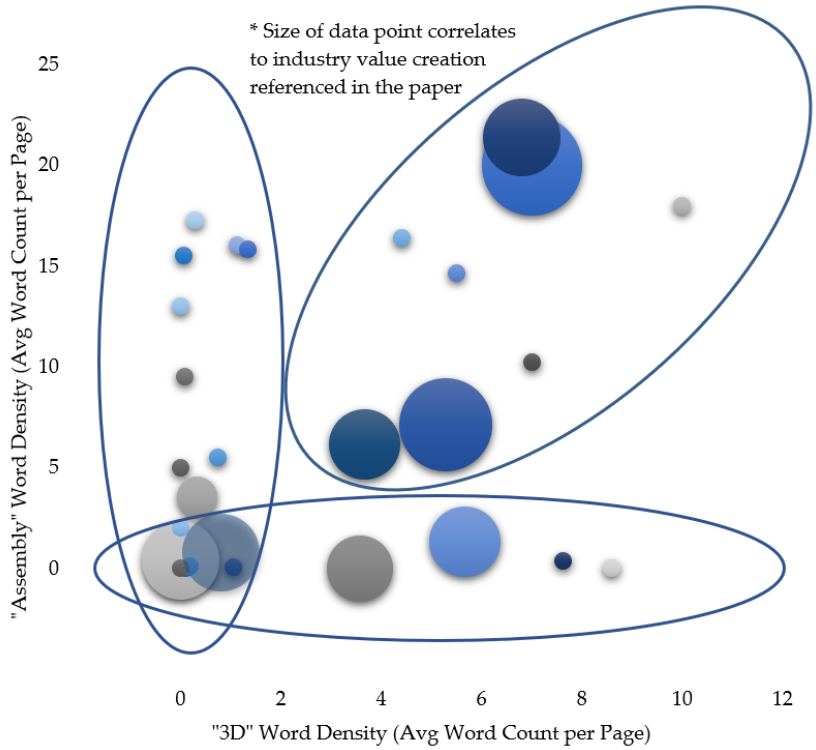

Figure 7. The 3D product model in the assembly process: literature review [1].

The principal contributions of this paper are development of the quantitative model and determination of quantitative value for the five areas of value creation when implementing the 3D product model in the assembly and production processes. As demonstrated by a review of the prior research literature, this research fills a gap in terms of creating a model for and associating a quantitative value with the deployment of the 3D product model in the production and assembly processes. While some research discusses how applying a 3D product model improves the efficiency and reliability of process planning [22], no quantitative data are given to support these findings. Thus, this paper looks to fill that gap by providing a quantitative analysis. Other papers do demonstrate quantitative value for implementing the 3D product model in the production process [18,23], but do so in the context of one company. Whereas this paper gathered input from and provides guidance to a quantitative value model applicable across manufacturing companies and industries. This research fills the gaps in existing research by developing a quantitative model for the value of deploying the 3D product model in the production and assembly process and delivers quantitative results. By delivering the quantitative model and quantitative results, this research then sets the foundation and focus for future work by academia and industry alike when researching and deploying the 3D product model to assembly and production processes.

Conclusions

While companies recognize that there is inherent value in applying the 3D product models beyond just product design, up to this point much of that value is still described in ways that were very qualitative in nature. This paper provides quantitative models to translate the qualitative value into numeric value. The quantitative value of implementing the 3D product model in assembly and production processes aligns with the qualitative value areas of focus in that all qualitative areas do in fact generate quantitative value. However, the magnitude of the value creation is different among the qualitative and quantitative results. Where the qualitative results showed the value generation to be in the following order (from the greatest value category to the least):

(1) Accuracy of assignment of the right parts, tools, work allocation, and work instructions;
(2) Faster new product/model roll out to production;
(3) Less time updating work instructions;
(4) Quicker operator training;
(5) Smoother transition for field use.

The quantitative results showed the value generation of implementing the 3D product model in the assembly and production process to be as follows:

(1) Accuracy of assignment of the right parts, tools, work allocation, and work instructions;

(2) Faster new product/model roll out to production;

(3) Smoother transition for field use;

(4) Quicker operator training;

(5) Less time updating work instructions.

The comparison of these results demonstrates that in both the qualitative and quantitative analysis the top two areas of implementing the 3D product model in production and assembly processes remained the same. This provides guidance for industry and academic practitioners alike in terms of a recommendation to focus future efforts in deploying and researching the implementation of the 3D product model use in production and assembly processes to the categories of: (1) Accuracy of assignment of the right parts, tools, work allocation, and work instructions, and (2) faster new product/model roll out to production. The discrepancy of the order of magnitude of value creation between the qualitative and quantitative model in Categories 3 through 5 also provide an area for future clarification and research. This additional research could include further validating the quantitative models by applying them against additional companies who have implemented the 3D product model in their production processes, to further calibrate the models accordingly. In addition, other considerations to be taken into account in future research include interactions between variables in the quantitative value calculation, aggregation of the value at the manufacturing plant and organization levels, loss of value created due to tradeoffs of retiring legacy processes while implementing the 3D product model in production and assembly processes, and further development of the cost of implementing and maintaining the 3D product model in the manufacturing process solution.

Author Contributions

C.K. and D.S. conceived the idea. C.K. formulated the problem, developed the quantitative model, and worked with industry participants to collect and calibrate the results. G.H. and D.S. provided guidance throughout the research and proofread the manuscript. All authors have read and agreed to this version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data presented in this study is available in Section 3 of the manuscript. Specific references have been generalized to protect the right of the industry experts (who collaborated in this research) to remain anonymous while still retaining the relevance of the data.

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Conflicts of Interest

The authors declare no conflicts of interest.

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CHAPTER 6. APPLIED RESEARCH ON ELECTRONIC DOCUMENTATION AND 3D PRODUCT MODEL DEPLOYMENT TO PRODUCTION AND ASSEMBLY PROCESSES

Carl Kirpes, Dave Sly, and Guiping Hu

Industrial and Manufacturing Systems Engineering (IMSE), Iowa State University

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Abstract

The three-dimensional (3D) product model has become a tool that has transitioned from a legacy instrument used in design to an emerging technology applied to production and assembly processes. As this evolution has occurred, the need has developed to understand the value of deploying the 3D product model beyond the design phase. This research answers the question, does electronic documentation inclusive of the 3D product model add to the production workers' ability to complete the production task? To answer this question, the research team tested how accurately and quickly a production and assembly team could build the product using interactive, electronic documentation, including the 3D product model, as a means to understand design intent as opposed to printed Bills of Material (BOMs) and paper two-dimensional (2D) drawings. The research found statistically significant improvements in production throughput time, reductions in direct labor hours per unit, and retained quality levels when deploying electronic documentation, including the 3D product model, to the production and assembly processes. Through the deployment of the interactive 3D product model electronic documentation to the production floor, the organization also took a step towards having a digital twin of the produced product and laid a foundation for further adoption of industry 4.0 practices. This research was conducted at an industrial equipment manufacturer, yet the methodology was documented so the

experiment is repeatable, ensuring other companies could benefit from the findings and application of this research.

Keywords

3D Product Model; Assembly; Process Planning Systems; Concurrent Engineering; Automotive Industry Applications; Manufacturing Industry Applications

Introduction

The 3D product model, once a tool used primarily for product design [1], has evolved to be able to create value beyond design in areas such as improving the efficiency and reliability of assembly process design, reducing process planning problems, and shortening the process planning cycle [2,3]. Up until the 2000s to 2010s, the ability to deploy the 3D product model to the assembly process was limited by software availability [4,5]. More recently, enabling factors have been removing these limitations [6] via transforming the engineering bill of materials (eBOM) into the manufacturing bill of materials (mBOM) [7-9]: the advent of manufacturing process management (MPM) systems [10], the ability to extract 3D product model data [11-16], and the growth in virtual manufacturing knowledge [17,18]. Building on these enabling factors, research has demonstrated that the 3D product model can be integrated with assembly line balancing via process consumption [19], be used as the link between the Bill of Process (BOP) and the Bill of Materials (BOM) [20,21], and check the products configuration for assemblability [22]. Through these applications, the 3D product model can be used to enhance shop floor work instructions, improve process planning, and increase assembly efficiency [23,24]. While the body of knowledge does demonstrate that deploying the 3D product model to the assembly process is now feasible and can be done so in ways that create value, the value is not described in numerical terms of economic (i.e., shareholder) value creation for organizations. Under this premise the authors have observed that while academic research maintains that deploying the 3D product model to the production and assembly processes creates value, those theoretical findings are not translating to definitive action in industry. This research will bridge that gap, taking and building on the value creation principles in academic research and translating those principles to an industry use case in which the value creation can be further substantiated.

With the development of the emerging technologies to deploy the three-dimensional (3D) product model to the production and assembly process, the opportunity exists for organizations in industry to capture value that was previously unattainable [20]. To align the authors' and the readers' understanding of value; Value is defined in this paper at its highest level as shareholder value, which can be further broken down in subcategories of value creation such as revenue growth, operating margin, asset efficiency, and shareholder expectations [25].

When deploying the 3D product model to the production and assembly process, key areas to focus on in capturing that value include [26]:

(1) Accuracy of assignment of the right parts, tools, work allocation, and work instructions;
(2) Faster new product/model roll out to production;
(3) Less time updating work instructions;
(4) Quicker operator training;
(5) Smoother transition for field use.

A quantitative model has also been developed which organizations can use to understand the incremental value that deploying the 3D product model creates in these areas [27]. However, a study has not been done on the interactions between variables in the quantitative value calculation, loss of value created due to tradeoffs of retiring legacy processes while implementing the 3D product model in production and assembly processes, or further development of the cost of implementing and maintaining the 3D product model in the manufacturing process solution [27]. Through applied research, the authors have collaborated with an industrial equipment manufacturer to further understand the impacts of deploying the 3D product model to the production and assembly processes.

The authors note that research does exist on the benefits that various BOM structures and product family configurations have on shop floor production metrics [28-30]. However, this paper will differ from those in that it will focus on the process flow for information to move from engineering to production in the presence of electronic documentation, and more specifically the 3D product model, as a means to communicate design intent from engineering to the production floor as opposed to printed Bills of Materials (BOMs) and paper two dimensional (2D) drawings. For clarity, the 3D product model is defined as the virtual computer aided design (CAD) model and digital assembly mock-up (as shown in Figure 1).

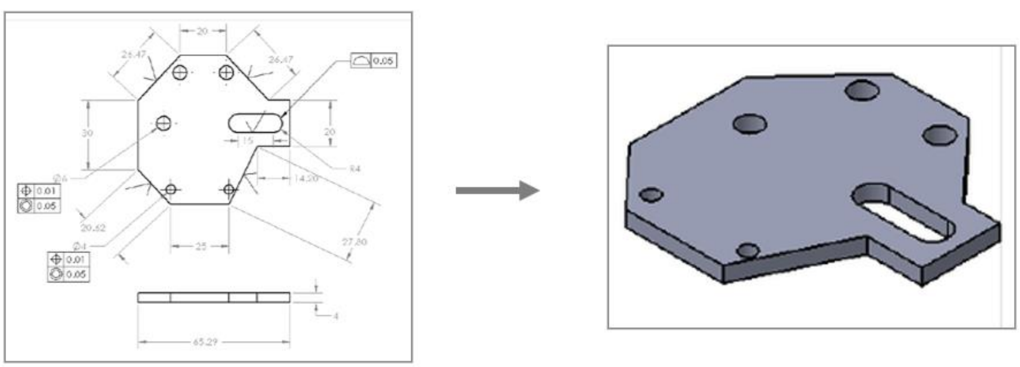

Figure 1: Moving from a 2D Drawing to a 3D Product Model

While prior research has focused on the legal, technical, and data requirements of moving to electronic documentation as a means of communication from engineering to the production floor, prior research concludes that additional research needs to be done on the cost savings benefits in order to garner broader industry adoption [5]. Much of the research in the current body of knowledge does not demonstrate a repeatable methodology through which industry and other researchers can replicate the experiment of demonstrating economic value when deploying the 3D product model to the production and assembly process. In this paper, the authors aim to build on prior work to demonstrate a repeatable methodology for determining the economic value of the 3D product model deployment to the production and assembly process through applied research.

The objective of this research paper is to fill the gap in the existing body of knowledge by demonstrating the incremental value (or lack thereof) that deploying the 3D product model to the production and assembly process can have over deploying the hard copy BOM and associated printed 2D drawings to the production floor and assembly processes. Laboratory research has shown improvement in operator assembly time when training operators on assembly processes when those operators are trained using the electronic guided assembly instructions over paper instructions [31,32], yet despite the academic research demonstrating the theoretical benefits, few studies exist demonstrating this value in an applied industry setting. This research will answer the question of whether electronic documentation inclusive of a 3D product model adds to the production workers' ability to complete the production task.

To answer this question, Section 2 discusses the materials and methods used by the research team to test how accurately and quickly a production and assembly team could build the product using interactive, electronic documentation, including the 3D product model, as opposed to the production team referencing printed BOMs and paper 2D drawings to build the product. Included in Section 2 is the experimental design along with a description of the process from when a manufacturing engineer receives the information for a new order through when the production workers receive and consume that information. Section 3 analyzes the data captured during the study and applies hypothesis testing to report on the statistical relevance of those findings. Section 4 and 5 includes a discussion of the research conducted at this industrial equipment manufacturer and documents how the methodology is repeatable, ensuring other companies can benefit from the findings and application of this research. The final sections of the paper also provide summary, conclusion, and future work.

Materials and Methods

Emerging Technology Studies

Before beginning the study, the authors reviewed other studies of applications of emerging technologies to businesses to see the metrics and processes used to determine if those technology and process deployments were successful. Studies on Enterprise Resource Planning (ERP) implementations, which determined financial metrics such as return on investment (ROI), return on assets (ROA), and others to evaluate the success of the ERP system [33] were found to provide a baseline approach to metrics that could be used in 3D product model electronic documentation deployment to the production and assembly process. However, given that the ERP performance measurement study used metrics at the highest level of the organization, other contributing factors could have played a large part in the metrics that may not have been attributable to the ERP implementation. As such, the approach of using key value metrics measured before and after the technology implementation were adopted in this paper with consideration for ensuring the metrics were tied to the emerging technology deployment.

The authors also reviewed a study in which a new process was introduced into the business rather than a new technology, specifically the introduction of an operational excellence program [34]. The team that focused on the operational excellence implementation developed specific profitability metrics that tied directly back to the operational excellence process [34]. While the study could have been enhanced by including a metric on throughput related to the operational excellence program, the specific metrics tied to profitability to measure the success of the operational excellence process were transferable to metrics that could be used when evaluating the value of the 3D product model electronic documentation deployment to the production and assembly process. Thus, the authors have taken a similar approach in this research to use targeted metrics tied back to profitability (and thus shareholder value) to determine the success of deploying the 3D product model as a means of communication on the design intent between manufacturing engineering and the production team members.

Production Unit Specification Information Flow

After reviewing adjacent technology and process implementation studies to develop a framework for this research, the research team began working with the industrial equipment manufacturer to understand the current state of the engineering and manufacturing operations. The objective was to understand the process for how the company communicated information on design intent from engineering to production without the use of the 3D product model beyond the initial design phase. When the research team began working with the manufacturer, the company was using the bill of materials released to the shop floor as the bill of process. The company had six product models, but each model could contain thousands of options. The BOM not only called out the model to be manufactured but also had all the options to be manufactured/assembled for that given piece of equipment. An example of a couple lines of the BOM that was released to the shop floor is shown in Figure 2.

Item	Item Description	Qty
1	GRP, SILL & TROUGH - 40'	1
2	GRP, ACCESS DOOR Hinged / Bolted	6
3	GRP, RACK & PINION (1)-60.00	8
4	GRP, BIRDHOUSE COVER	8
5	GRP, BULKHEAD EXTENSIONS	9

Figure 2: Example of line items on the Bill of Materials (BOM)

The research team first aimed to gain an understanding of the baseline process for communicating information from engineering to production before determining where electronic documentation, inclusive of the 3D product model, would best be deployed. The process in which the BOM was created started with the sales representative who worked with the customer to determine the model type and options that the customer would like on their unit. The sales process not only included inputs from the customer's wants and needs, but also the translation of those wants and needs into the corresponding unit model and options based on the sales representative's expertise. The information was input into a configurator by the sales representative, which generated a baseline BOM and translated that information into a quote. The sales representative could also add custom options that had never been designed before. Once the customer and sales representative reached an agreement on the model, options, and price, the quote was signed. The customer then placed a down payment or a purchase order which kicked off the process internally at the manufacturer of translating that initial design concept into a manufacturable BOM and drawing set. The internal process for after a quote became an order is shown in Figure 3.

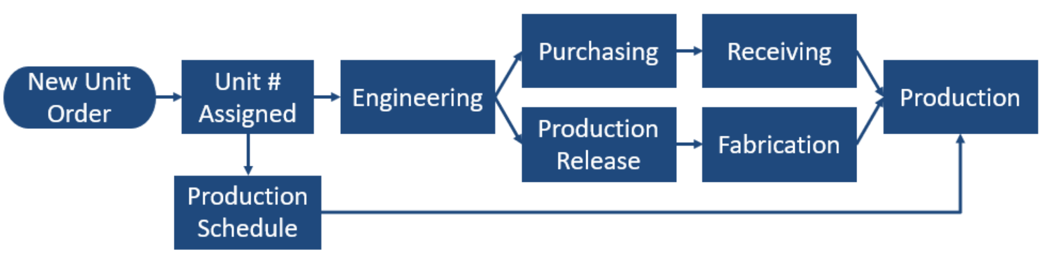

Figure 3. Baseline State Manufacturing Engineering Information Flow to Production

When a quote became an order, that resulted in a transaction where a new unit (or set of units) was agreed to be purchased and sold. To create a unique identifier for each unit, a unit number was assigned. This unit number acted as the unique reference key for the unit and was included in all stages of the unit's life cycle, from production to later serving as reference for future parts and service work orders.

Once a unit number was assigned, the paperwork for that unit moved to the engineering team and scheduling team. The engineering team took the information developed by the sales representative and turned that information into a manufacturing bill of materials (mBOM) and associated 2D drawing package. While the engineering team had the capability to create 3D models, this technology was not used beyond the initial design phase when this study began. All information that was translated to production and purchasing was primarily in the form of the BOM with 2D drawings of newly designed options and features. The scheduling team was also informed when a unit number was assigned so that the build of the unit could be slotted into the production schedule.

Once engineering finalized the BOM and 2D drawings, this information was released to both purchasing and production. The purchasing team sourced the purchased components needed to build the industrial equipment. These purchased items were then received by the shipping and receiving team, and production was notified when those components arrived. For production, the BOM and 2D drawings were reviewed to ensure that the information released was manufacturable (e.g., there were not two options in the BOM intended to be placed in the same space on the produced unit). The production supervision team then decided which drawings needed to be printed to be given to the production and assembly team along with the printed BOM. The baseline process had no formal way for engineering to communicate to production other than through these channels.

The production supervision team then passed off the BOM and the selected printed drawings to the fabrication team. The fabrication team built the internal parts and subassemblies needed to produce and assemble the unit. At this stage, the externally purchased components were also being received. These fabricated subassemblies and purchased components then flowed to the production team along with the BOM and 2D drawings. The production team used the fabricated components, purchased components, hard copy 2D drawings, and printed BOM to produce and assemble the unit. These activities were all synchronized to align with the key dates listed in the production schedule that were developed back when the unit number was assigned (i.e., when the new unit order from the customer was received).

As Figure 3 and the process description above demonstrate, the link between engineering and production flowed through intermediary steps before reaching production. Nowhere in this process was the 3D product model used other than in the initial product design. Drawings were not available to the operators unless the engineering team and production supervisors released specific 2D paper drawings with the paper bill of materials for new features. All other models and options that needed to be manufactured/assembled on the unit were either understood by the operator through the information they read on the BOM, based on their experience having built similar model and option combinations previously, or through discussions with the engineers. The BOM, which was the primary means of communication between engineering and production, traveled with the unit being produced through the production and assembly process, which is shown in Figure 4.

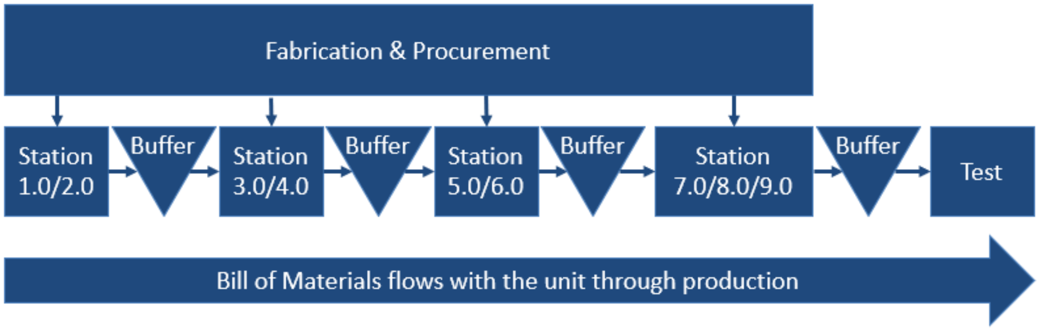

Figure 4. Unit production and Bill of Material Flow through the production & assembly process

The operators did not have access to computers on the shop floor, so they would either walk into the engineering office to request clarification/2D prints or use a two-way radio to request that an engineer come out to the production floor to answer their question. Given that the company has experienced low turnover in the prior 5+ years, operator experience played a key factor in being able to successfully build units with varying model and option combinations based on knowledge gained from that previous experience. Figure 5 shows the tenure of the workforce at this location.

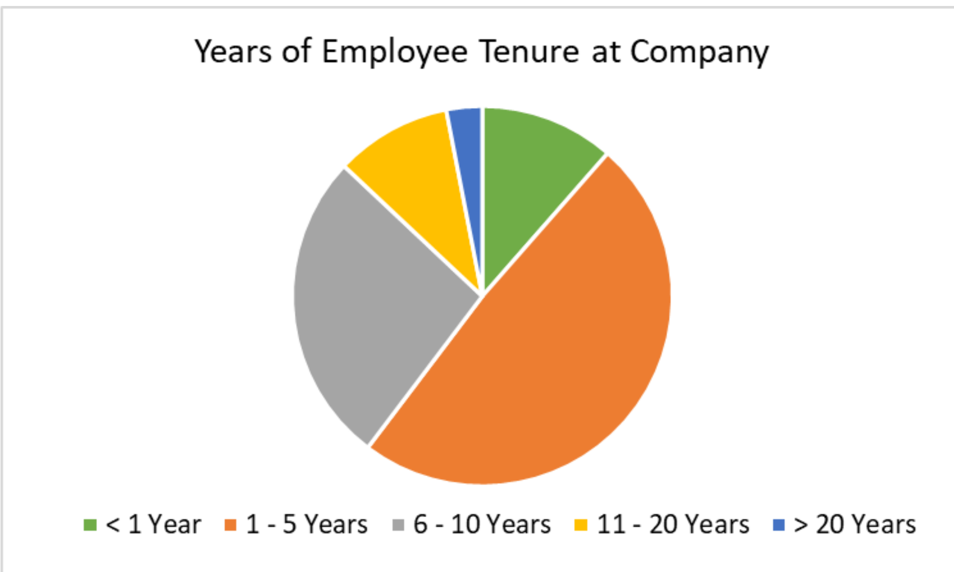

Figure 5. Employee Tenure at Company (where research was completed)

Adding Electronic Documentation, Inclusive of the 3D Product Model, to the Production Process

After understanding the baseline product specification information flow from a new unit order at this industrial equipment manufacturer, the research team analyzed where deploying the 3D product model would add value. The manufacturing facility has a production line where different operators perform different tasks. This research scope focused on deploying electronic documentation inclusive of the 3D product model via a virtual interface (a computer on the production floor) to two of the stations (1.0/2.0 and 3.0/4.0) on the production line. The intent was to provide the operators with a visual 3D representation of the portion of the product they were responsible for building, so that they could visually see the impact that the model and option combination had on their station on the assembly line. The hypothesis was that the production process would improve via the production and assembly workers having direct access to the 3D product model in the production process. The expected benefits included: Accuracy of assignment of the right parts, tools, work allocation, and work instructions; Faster new product/model roll out to production; Less time updating work instructions; Quicker operator training; and Smoother transition for field use. These benefits were anticipated to result in improved throughput, fewer direct labor hours per unit, and a reduction in quality defects on the units produced. Based on these hypotheses, the research team recommended deploying electronic documentation, inclusive of the 3D product model, to the production floor.

Even though most employees were able to use prior experience to successfully build the units, the company leadership agreed that having electronic documentation, including the 3D product model, available to the workforce at this division would be a good system to put in place. Such a system was projected to help current and future operators (that would inherently have less experience on previously built model option combinations) learn the production/assembly process more quickly and possibly produce fewer errors and quality defects by having the 3D product model available for reference. For example, the 3D product model could be directly displayed on the shop floor via a computer screen allowing the operator to interact with the model as the unit is being assembled and produced. This enabled engineering to directly convey the design intent to the production floor through electronic documentation, including the 3D Product Model, as shown in Figure 6.

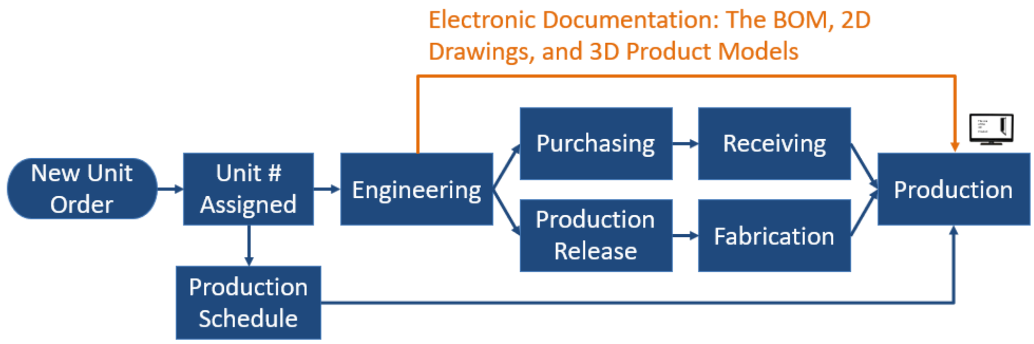

Figure 6. Future State (Phase 1 & 2) Manufacturing Engineering Information Flow to Production

When deploying the electronic documentation to the production and assembly process, the research team specifically focused on stations 1.0/2.0 and 3.0/4.0. These stations were selected based on discussions with the company that these operations were the bottleneck in the manufacturing process. As such, if the takt time of these stations improved, the takt time of the full manufacturing process would improve (subject to this bottleneck not improving past the point that the takt times at station 1.0/20 and station 3.0/4.0 became less than another station). This changed the process flow in Figure 4 to Figure 7, with the addition of the computers to deploy the electronic documentation to the shop floor. The interactive nature of the 3D product model and electronic documentation, and its deployment to the production floor, also was a step towards this manufacturer creating a digital twin of the units being produced and set the stage for the company evolving into an organization that embraces Industry 4.0.

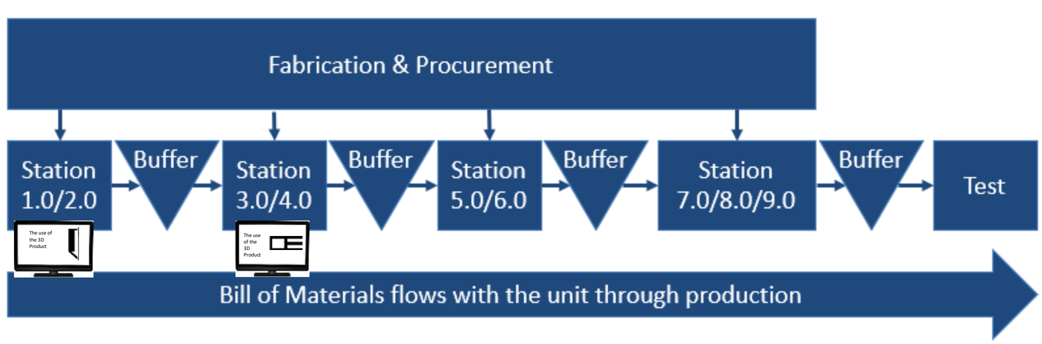

Figure 7. Unit production flow with electronic documentation added at station 1.0/2.0 and 3.0/4.0

Experimental Design

Once the hypotheses to be tested were agreed upon between the research team and company leadership, an experiment had to be created to test the hypotheses. To determine the impact of deploying the electronic documentation to the production and assembly processes, the authors compared the scenario with and without the 3D product model electronic documentation. In both scenarios, the research team measured the quality and speed with which the production team was able to assemble and produce the unit. The experimental design followed Table 1.

Table 1. Manufacturing Engineering Information Flow to Production Experimental Design

	Manufacturing Engineering to Production Information Flow	
	Current (Baseline) State	Future (Phase 1 & 2) State
Independent Variables	Printed BOM & 2D Drawing (Station 1.0/2.0 and Station 3.0/4.0) 5 to 15 units	Electronic Documentation: The BOM, 2D Drawings, and 3D Product Model (Station 1.0/2.0 and Station 3.0/4.0) 5 to 15 units
Dependent Variables	Throughput (Time in Jig), Production Labor Hours (Direct Labor on a Unit), and Quality of Assembly/Production (Defects per Unit)	
Control Variables	Operators, Manufacturing Environment, Production Tools & Equipment, Type of Production Unit, Management, Engineering, Learning Curve, Hawthorne Effect	

Once the experimental design was agreed upon, the methods that would be used to collect data had to be established. Before deploying the 3D product model to the production floor, the research team started by measuring the standard times of the production team at stations 1.0/2.0 and 3.0/4.0 to produce units under the baseline process, with the BOM and some 2D drawings available. The measurements included the throughput time of units through these stations, the direct labor hours at these stations, and the quality defects attributable to these stations. The research team then deployed the electronic documentation, including the 3D product model, to the production process and remeasured all these key metrics. The throughput time of the units was measured based on the duration that each unit was in the jig. This data was captured through video observations, as shown in Figure 8. Over 1,600 hours of video data was recorded and over 1,200 hours of video data was analyzed. The video that was analyzed was the time that the units being studied were at station 1.0/2.0 and station 3.0/4.0. Video that was recorded but not analyzed was comprised of times when the manufacturing facility was not in operation (e.g., recordings made on Saturday evenings and Sundays).

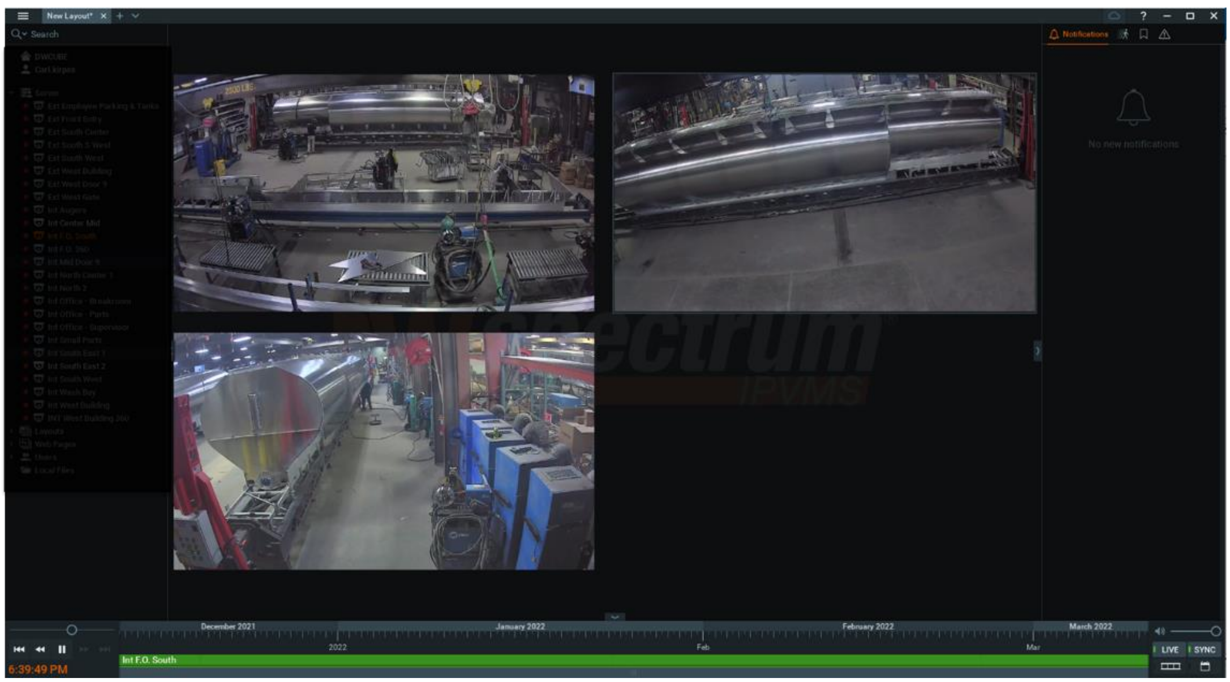

Figure 8. Video software used for observation and data collection

Direct labor hours were measured through timecards filled out by each operator at each station noting the amount of time that they worked on each unit. The company reconciled these timecards against the operator’s timeclock information of when they punched-in and punched-out to ensure accuracy of the timecard data, which gave the research team confidence in the accuracy of the information. The research team then aggregated the timecard data to determine all the direct labor hours by unit by station.

Any quality defects that require rework are captured through documentation on a red sheet of paper that travels with the unit. The defects are corrected prior to the unit leaving the manufacturing facility. These quality items can be identified throughout the process or in the final stages of quality inspection and testing. The documentation of the quality defects on the units in this research were reviewed to determine if the quality defect occurrences changed after the implementation of the 3D product model electronic documentation.

The research team also accounted for control variables through the research study and data collection process. Baseline factors such as the operators working at the stations, the manufacturing environment they were working in, the management team, the engineering team, and the access to production tools & equipment were all set to be the same across all phases of the study. Thus, these factors were not changed when the sample data was collected. To control against the learning curve, the baseline data was used to establish a learning curve and then extrapolated across future units to test if there was an improvement in the production throughput time and direct labor hours when accounting for the continuation of that learning curve. For controlling against the Hawthorne effect [35], the facility has had cameras installed for over five years prior to this study, so the operators were accustomed to the cameras being in place. Data collection was only done through observation on these cameras and in post-process documentation review such that the operators were not aware the units in this study were being observed. While the operators were aware of the changes being made in the production process through the implementation and training on the use of the electronic documentation and 3D product models, the operators were not aware that observations were being made via the cameras and post-process documentation regarding changes in throughput, direct labor hours, and quality. Thus, the fact that the production of those units was being observed would not have an impact on the results.

Ultimately, the objective was to understand how quickly and accurately a new unit could be produced with the operators having access to electronic documentation, including the 3D product model, versus using only printed BOMs and 2D drawings to understand the design intent while controlling for other variables.

Experimental Set-up

Once the methods were determined that would be used to collect data, the experiment had to be set-up to structure the data in a way that would align with the experimental design. The data collection plan is shown in Table 2. The research team collected data in the Baseline Phase without the electronic documentation deployed to the production floor. In Phase 1, a computer inclusive of electronic 3D documentation was implemented at station 1.0/2.0 and one of the two 3.0/4.0 stations (3.0/4.0 North). In Table 2 below, this can be seen in Phase 1 samples 12-15, where electronic documentation was at station 1.0/2.0 as well as station 3.0/4.0 North, but not at station 3.0/4.0 South. Phase 1 is also when operators were trained on how to access the electronic documentation and use the information. In Phase 2, all stations (1.0/2.0, 3.0/4.0 North, and 3.0/4.0 South) had a computer deployed to the shop floor with the needed electronic documentation software and access to 3D product models. The Baseline Phase was used for the current state analysis. Both Phase 1 and Phase 2 units and associated throughput time, direct labor hours, and quality were included as a part of the future state.

Table 2. Electronic documentation, including 3D product model, deployment to production

	Unit #	Research Phase	1.0/2.0 Electronic Documentation	3.0/4.0 Station	3.0/4.0 Electronic Documentation
1	1450	Baseline	No	North	No
2	1451	Baseline	No	South	No
3	1452	Baseline	No	South	No
4	1453	Baseline	No	North	No
5	1454	Baseline	No	South	No
6	1449	Baseline	No	South	No
7	1455	Baseline	No	North	No
8	1456	Baseline	No	South	No
9	1457	Baseline	No	North	No
10	1458	Baseline	No	South	No
11	1459	Baseline	No	North	No
12	1460	Phase 1	Yes	South	No
13	1461	Phase 1	Yes	North	Yes
14	1462	Phase 1	Yes	North	Yes
15	1463	Phase 1	Yes	South	No
16	1512	Phase 2	Yes	North	Yes
17	1513	Phase 2	Yes	South	Yes
18	1514	Phase 2	Yes	North	Yes
19	1515	Phase 2	Yes	South	Yes
20	1516	Phase 2	Yes	North	Yes
21	1517	Phase 2	Yes	South	Yes
22	1518	Phase 2	Yes	North	Yes
23	1519	Phase 2	Yes	South	Yes
24	1520	Phase 2	Yes	North	Yes

Results and Analysis

Difference in Means Results and Analysis

The results that follow use the data collected on throughput times, production labor hours, and quality defects per unit and compare the results before the electronic documentation was deployed (Baseline) as compared to after (Phase 1 & Phase 2). The data was collected across multiple months as each station can only have one unit being processed at a time and each unit takes multiple working days with multiple operators to produce. This led to a smaller sample size, yet even with the smaller sample size the research team was able to obtain conclusive results. The tables below show the sample size, sample mean, and sample standard deviation (Std Dev), when compared to without (w/o) and with (w/) electronic documentation (Elec Doc) at stations 1.0/2.0 and 3.0/4.0. Table 3 shows the comparison for throughput times, Table 4 shows the comparison for direct labors hours, and Table 5 shows the quality defects per unit comparison.

Table 3. Electronic documentation, including 3D product model, deployment throughput hours

Statistics	**1.0/2.0 w/o Elec Doc**	**1.0/2.0 w/ Elec Doc**	**3.0/4.0 w/o Elec Doc**	**3.0/4.0 w/ Elec Doc**
Sample Size	10	13	11	10
Mean	23.62	17.95	38.09	28.35
Std Dev	6.96	4.26	17.21	6.68

Table 4. Electronic documentation, including 3D product model, deployment direct labor hours

Statistics	**1.0/2.0 w/o Elec Doc**	**1.0/2.0 w/ Elec Doc**	**3.0/4.0 w/o Elec Doc**	**3.0/4.0 w/ Elec Doc**
Sample Size	11	13	13	10
Mean	43.90	36.05	87.77	64.00
Std Dev	9.88	9.21	9.79	13.16

Table 5. Electronic documentation, including 3D product model, deployment quality defects/unit

Statistics	**1.0/2.0 w/o Elec Doc**	**1.0/2.0 w/ Elec Doc**	**3.0/4.0 w/o Elec Doc**	**3.0/4.0 w/ Elec Doc**
Sample Size	11	13	13	10
Mean	0.45	0.38	0.31	0.60
Std Dev	0.69	0.65	0.63	0.70

Using the sample size, mean, and standard deviation for the metrics at each of the two stations, three hypothesis tests were run across each station to test the difference in means in throughput time, direct labor hours, and quality. This resulted in a total of six hypothesis tests. Table 6 demonstrates the null and alternative hypothesis for each metric of interest across each station.

Table 6. Hypothesis testing by station (1.0/2.0 and 3.0/4.0) by metric of interest (throughput time, direct labor hours, and quality measured in defects per unit)

Hypothesis Tests	Null Hypothesis	Alternative Hypothesis
Station 1.0/2.0		
Throughput time…	…w/ Elec Doc ≥ w/o Elec Doc	…w/ Elec Doc < w/o Elec Doc
Direct Labor Hours…	…w/ Elec Doc ≥ w/o Elec Doc	…w/ Elec Doc < w/o Elec Doc
Quality…	…w/ Elec Doc ≥ w/o Elec Doc	…w/ Elec Doc < w/o Elec Doc
Station 3.0/4.0		
Throughput time…	…w/ Elec Doc ≥ w/o Elec Doc	…w/ Elec Doc < w/o Elec Doc
Direct Labor Hours…	…w/ Elec Doc ≥ w/o Elec Doc	…w/ Elec Doc < w/o Elec Doc
Quality…	…w/ Elec Doc ≥ w/o Elec Doc	…w/ Elec Doc < w/o Elec Doc

Table 7 then shows the difference of means in the cases with and without electronic documentation to determine if there is a true difference in the mean throughput time, mean production labor hours, and mean quality defects. The results in Table 7 were calculated using one sided t-tests for the difference of means with different sample sizes.

Table 7. Electronic documentation, including 3D product model, deployment difference of means (Δ = not significant so fail to reject the Null, * = significant at .1 level, ** = significant at .05 level, *** = significant at .025 level, **** = significant at .01 level)

Difference in Means w/o vs w/ Elec Doc	Throughput (hours)	Direct Labor (hours)	Quality (defects/unit)
Station 1.0/2.0	5.67 ***	7.85 **	0.07 $^{\Delta}$
Station 3.0/4.0	9.73 *	23.77 ****	-0.29 $^{\Delta}$

The difference in means for quality at both station 1.0/2.0 and 3.0/4.0 were not significant and therefore the null hypothesis failed to be rejected. Therefore, the conclusion cannot be drawn that quality improved after the electronic documentation deployment to the production process. The difference in means results for throughput and direct labor hours at both stations 1.0/2.0 and stations 3.0/4.0 do show results with levels of significance which vary as indicated by the asterisks in Table 7. Therefore, the conclusion can be made that there is a difference in the mean throughput times and the mean direct labor hours when comparing the base case to the deployment of the electronic documentation to the shop floor. However, these results do not account for the learning curve, which is one of the variables the research team planned to control for when determining the result of the experiment. As such, the results need to be compared when accounting for the learning curve. Additional statistical analysis was run accordingly.

Learning Curve Results and Analysis

Figure 9 shows a sample of the baseline data collected for station 1.0/2.0 throughput times with a learning curve fit to the data. The learning curve equation is Y = K * X ^ n [36]. In the regression-curve fit to the data below, we can see that K = 27.279 and n = -0.112 (which is the learning curve factor). The learning curve factor, n, is equal to the natural log of the learning rate divided by the natural log of 2, so a n of -0.112 equates to a learning rate of 92.5%. A 92.5% learning rate is the same as a 7.5% improvement rate, meaning that each time the operator performs the task the operator does the task 7.5% better/faster than the time before. Given that the operators at this company are experienced at performing this production and assembly process, and this study is introducing the operators to a new model-option combination (versus a whole new product or whole new operation), the 7.5% improvement rate is reasonable.

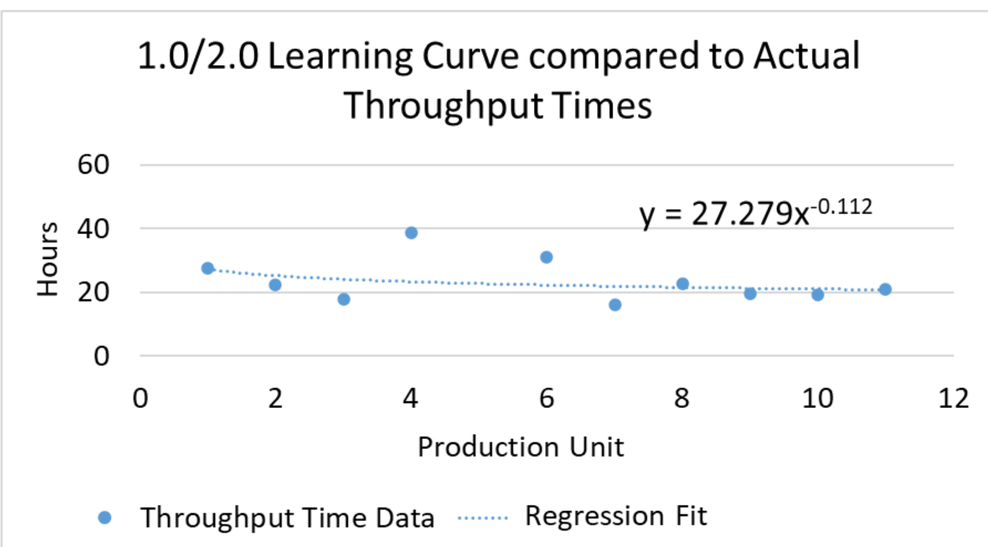

Figure 9. Learning curve applied to baseline data

Using the 7.5% improvement rate from the learning curve, the learning curve can then be extrapolated from the data collected in the baseline case where no electronic documentation or 3D product models were available to the operators. This extrapolation can be used to determine how the production throughput times and direct labor hours would have improved if that state were to have continued without the deployment of the electronic documentation to the shop floor. The solid line in Figure 10 shows an example of the extrapolation of this learning curve when applied to the 1.0/2.0 throughput times.

Of note is that some of the data points had hours in the jig that were significantly above the others, specifically unit 1453 and unit 1449 for the units without electronic documentation, and units 1512 and 1513 for the units with electronic documentation. When the operators would receive information in the baseline state where electronic documentation was not accessible, if they had questions on the build of the unit based on the models and options available then they would either go to engineering to discuss or call an engineer out to the floor. The time taken in this process would result in incremental time in the jig as the unit sat while the operators and the engineers worked to connect with each other, understand the challenges, and get them resolved. These challenges occur and are a natural part of the production process, so the research team felt that including data points representative of those challenges was relevant to capture the natural variation in the production process. In the state where 3D electronic documentation was available to the operators on the production floor, the production team was able to access this electronic documentation to resolve most of the questions they had on model or option questions for the build. While these questions arising (and the time it took for the operators to resolve them) still added to the time the unit was in the jig, the observed increase in the time to resolve the issue was significantly less as the operators had direct access to the information from engineering without having to track down and discuss with a specific engineer. The operators still experienced increased time the unit was in the jig when such questions on how to accurately perform the unit build arose, however, the needed information was clarified sooner as a result of the operators access to the electronic documentation in most cases.

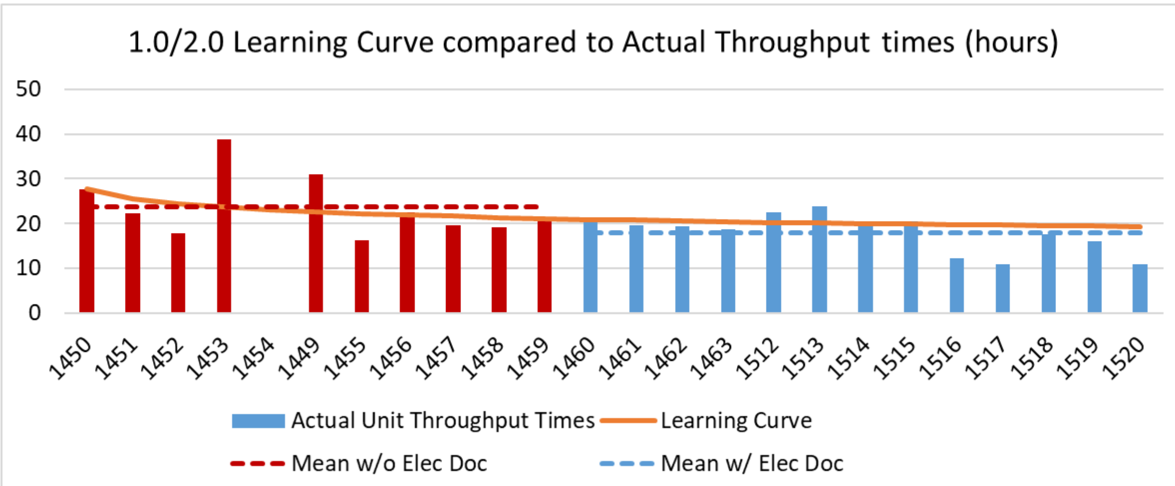

Figure 10. Extrapolating the Learning Curve and comparing to mean times

To show that the electronic documentation, inclusive of the 3D product model, had an improvement in these throughput times, the difference in means has to be such that the new mean after the electronic documentation is deployed to the shop floor is an improvement over what the learning curve alone would have accounted for. To visually demonstrate this improvement, the first dashed line in Figure 10 is the mean 1.0/2.0 throughput time without electronic documentation, and the second dashed line is the mean throughput time with electronic documentation. Given the second dashed line is below the projected learning curve line, the graph shows what appears to be an improvement in the mean throughput times after the electronic documentation is deployed beyond what the learning curve alone would explain. However, just visually demonstrating that the mean throughput time is below the projected learning curve does not necessarily mean that the improvement is statistically significant. The research team ran hypothesis tests to better determine the statistical significance of the perceived improvements.

Hypothesis Testing Results and Analysis

To run statistical analysis on the perceived improvements in throughput and direct labor hours after deploying the electronic documentation to the production floor, the team set-up hypothesis tests. In the case of throughput times, the null hypothesis (H0) was that the electronic documentation mean throughput time is equal to or greater than the throughput time without electronic documentation when accounting for the learning curve. The alternative hypothesis (H1) was that the electronic documentation mean throughput time is less than the throughput time without electronic documentation when accounting for the learning curve. This created a one-sided hypothesis test. Rather than use the mean throughput time without electronic documentation as the hypothesis constant, the research team used the mean throughput time of the extrapolated learning curve as the hypothesis constant. This way, the learning curve was factored into the analysis and proving the alternative hypothesis to be true would show that the electronic documentation, inclusive of the 3D product model, reduced the mean throughput time beyond what the learning curve accounted for.

Similarly, in the case of direct labor hours, the null hypothesis (H0) was that the electronic documentation mean direct labor hours per unit is equal to or greater than the direct labor hours per unit without electronic documentation when accounting for the learning curve. The alternative hypothesis (H1) was that the electronic documentation mean direct labor hours per unit is less than the direct labor hours without electronic documentation when accounting for the learning curve. Like in the throughput hypothesis test, the research team used the extrapolated learning curve mean direct labor hours per unit as the hypothesis constant and structured a one-sided hypothesis test.

The improvement (and percentage improvement) that the electronic documentation mean was better than the extrapolated learning curve mean for throughput and direct labor at both stations 1.0/2.0 and 3.0/4.0 are below in Table 8. The table also highlights the significance level of each improvement. Given all areas showed significance at the 0.1 level or better, we accept the alternative hypothesis and reject the null.

Table 8. Electronic documentation, including 3D product model, deployment hypothesis testing mean improvement (& percentage improvement) accounting for the learning curve (* = significant at .1 level, ** = significant at .05 level, *** = significant at .025 level, **** = significant at .01 level)

Hypothesis Testing	Throughput Improvement	Direct Labor Hours Improvement
Station 1.0/2.0	2.11** (10.52%)	5.46** (13.14%)
Station 3.0/4.0	2.74* (8.80%)	12.82**** (16.68%)

The statistical analysis demonstrates that, when accounting for the learning curve, the deployment of electronic documentation, inclusive of the 3D product model, improves the throughput time and reduces the direct labor hours at both stations 1.0/2.0 and 3.0/4.0. As shown previously when running the difference in means calculation, this improvement had no adverse impact on product quality.

Translating the results to economic (shareholder) value

As demonstrated in Table 8, the throughput across station 1.0/2.0 and 3.0/4.0 increased by 10.52% and 8.80% respectively. For the production line, the throughput can only increase when the throughput of the bottleneck operation increases. At this industrial equipment manufacturer, although station 1.0/2.0 saw a greater improvement in throughput time, station 3.0/4.0 improvement being less resulted in station 3.0/4.0 remaining as the bottleneck operation.

As a result, the throughput of the production line is driven by the improvement across station 3.0/4.0. However, each unit across 3.0/4.0 taking 8.80% less time in the station actually results in a total throughput increase of 9.65%, as each unit moving through the station quicker also creates the opportunity for incremental units to be produced within a set time frame (e.g., one year).

In addition, direct labor hours decreased by 13.14% at station 1.0/2.0 and 16.68% at station 3.0/4.0. The direct labor hour reduction creates capacity across both stations at the baseline workforce level. With the implementation of the 3D product model and associated electronic documentation, even when accounting for the learning curve, the reduction in direct labor hours creates capacity and allows for work activities at the station to be consolidated among fewer operators. This frees up an operator to focus on work in other areas of the plant or removes the need to replace associates when attrition occurs because fewer direct labor hours per unit are required. However, direct labor hours can only truly be recognized as value added to the company when they allow for reduction in labor at an activity level, which is a level of work that can be transferred from one station to another. When applying this logic, the result is a combined 14.29% reduction in direct labor hours at this industrial equipment manufacturer.

By being able to produce more units with less direct labor via the electronic documentation deployment, inclusive of the 3D product model, this research demonstrates a way for manufacturers to increase revenue and profitability. For the manufacturer in this study, the data shows a throughput increase of 9.65% while simultaneously being able to reduce the direct labor hours by 14.29% and maintaining the same level of quality. This leads to a 6.75% increase in revenue and over a 10% increase in profitability.

Discussion

By deploying electronic documentation, inclusive of the 3D product model, to the production and assembly process the operators had more direct access to the engineering design intent for new product model option combinations. This resulted in the operators having accurate information on how the product was to be assembled and produced. The improvement in information flow between engineering and production via the electronic documentation resulted in improved throughput times with less direct labor hours per unit while demonstrating no negative impact on quality.

The authors note that, if this study were to be repeated, the tenure of the employees is likely to influence the magnitude of the impact of deploying the 3D product model to the production and assembly process. The authors anticipate that the benefits of implementing the 3D product model at a location with significant tenure in the workplace may show less value than at an organization with a less experienced workforce. The reason the authors would believe this to be true is that a less experienced workforce may benefit more from the information the 3D product model electronic documentation provides to the production floor as some of that information the experienced worker may already know as a result of their experience. The manufacturer that the authors worked with in this study had strong tenure in the workplace, and the results still show a positive impact on production throughput and direct labor hours while maintaining quality when deploying electronic documentation, inclusive of the 3D product model, to the production floor. Thus, additional upside beyond what this study shows may be available for manufacturers with a less tenured workforce who undertake the effort to deploy the 3D product model to the production and assembly processes. Additional research would need to be done at the other manufacturers to support this theory, which provides an opportunity for future research.

Future research could also take a deeper dive into the decisions that the operators are making during the production processes. This research would include evaluation of the operators' decisions, whether the 2D or 3D model is better serving the purpose of making the decision on a decision-by-decision level and provide justification behind the ratings for each decision on why a 2D or 3D product model served the operator better in making that decision. This would move the analysis from the production process and company level down to the individual operator level to show what decisions the operator is making using the electronic documentation inclusive of the 3D product model and how those decisions are generating improvements to the production process and company level results.

Summary and Conclusions

The implementation of electronic documentation, inclusive of the 3D product model, demonstrates a statistical improvement in both throughput times and reduction in direct labors hours while having no adverse quality impacts. This statistical improvement was shown using difference in means and then hypothesis testing while accounting for the learning curve. Thus, the research answers the question "does electronic documentation inclusive of the 3D product model add to the production workers' ability to complete the production task?" with an answer of "Yes."

This research fills a gap in the body of knowledge through applied research on the value of deploying 3D product models to production and assembly processes. The research takes academic concepts developed by the research team and others and demonstrates to industry and academia that true value creation is attainable when deploying electronic documentation, inclusive of the 3D product model, to production and assembly processes.

For this industrial equipment manufacturer, deploying the 3D product model to the production and assembly process also kicks off a journey that moves them closer to having a digital twin of the product being produced on the production floor and sets the stage for advancements towards becoming an organization that embraces industry 4.0.

Author Contributions

C.K. and D.S. conceived the idea. C.K. and D.S. formulated the problem. C.K. developed the research methodology and analysis that led to the conclusions. G.H. and D.S. provided guidance throughout the research and proofread the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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CHAPTER 7. GENERAL CONCLUSION

The 3D product model, once a tool primarily used in product design, has been demonstrated in this dissertation to have quantitative value when applied to the production and assembly process. Even when accounting for the learning curve of operators, the 3D product model deployment to the production and assembly process showed statistically significant improvement in throughput time and direct labor hours with no detriment to quality. The value demonstrated in this applied research is built on a quantitative model that derived five key value areas from a qualitative study on the deployment of the 3D product model to the production process. These areas included 1) accuracy of assignment of the right parts, tools, work allocation and work instructions, 2) faster new product/model roll out to production, 3) less time updating work instructions, 4) quicker operator training, and 5) smoother transition to field use. In addition, key to this research was a systematic literature review showing the research evolution of the 3D product model, synthesizing (16) research themes from that research evolution and determining future research trends. The 3D product model, when used by organizations in conjunction with managing the bill of process, becomes an emerging technology enabled systems approach to streamline the enterprise. This research answers the question, does the 3D product model provide value when deployed to the production and assembly process with a resounding “Yes!” and does so in a way that the methodology is repeatable for industry and academia alike. By closing this gap in the body of knowledge, this research lays a foundation for the deployment of interactive 3D product model electronic documentation to the production floor, and with it lays the groundwork for organizations to take a step towards having a digital twin of the produced product and creates a springboard for further adoption of industry 4.0 practices.