INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

DESIGNING A SMART ASSEMBLY SYSTEM

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ABSTRACT
This paper introduces and discuses the concept of smart assembly systems. Smart assembly seeks to transform the way in which products are designed and assembled based on the integration of virtual and real time assembly methods. The main goal of this paper is to initiate a discussion about the current needs for innovation around assembly systems and how new technologies are redefining the challenges of designing new assembly products and processes. The key elements identified for a smart assembly environment fall under the headings of people, product, process, technology, and information. A secondary part of this paper is the presentation of a roadmap for the development of the smart assembly vision. This roadmap considers the need to identify current roadblocks and enablers that will allow the presented vision to become a reality in the short term.

Keywords: Assembly systems, design for assembly, smart assembly

1 INTRODUCTION
In recent years, manufacturing operations in the U.S. have seen an increasing trend towards outsourcing operations to low cost manufacturing countries. This trend has significantly changed the way in which products are manufactured and assembled, with supply chain management gaining a fundamental role in the design of new products. A closer look at the outsourcing trend shows that low cost, simple, and small products are being produced completely offshore. However, complex, high-end, and specialty products are still being designed and manufactured in the U.S. In addition, even though the fabrication of many of their components has moved offshore, the assembly operations of automobiles and other large, complex equipment remain strong in the U.S. Similar trends are occurring in other developed nations, whether they are doing this assembly in their own country or in the developed nations in which the products are sold.

Unfortunately, as developing nations continue to progress technologically, to remain competitive and avoid the migration of these remaining assembly operations to lower cost countries, the entire notion of assembly operations must change to ensure unbeatable cost, quality, and delivery. This is not an easy challenge, assembly has to be completely rethought in terms of the product, the process, and the systems, simultaneously considering all aspects and taking advantage of the operations advances that do exist in developed nations. To this end, the concept of smart assembly brings new opportunities to maintain the relative advantages of assembly in developed nations – technology and training. Smart assembly therefore embodies the challenge – *what do assembly systems need to look like if there is still going to be assembly operations in developed nations?*

In 2006, during a National Institute of Standards and Technology (NIST) workshop in Smart Assembly (SA), Dr. Robert Tilove from General Motors gave the following definition for smart assembly systems, "SA refers to a next generation capability in assembly systems and technologies which integrate *virtual* and *real-time* methods in order to achieve dramatic improvements in productivity, lead-time, and agility for the design, engineering, validation, construction, installation, launch and operation of assembly processes and systems."

The intention of this paper is to begin the discussion about the current needs for innovation around assembly systems and how new technologies are redefining the challenges of designing new assembly products and processes. The paper focuses on the challenges of a smart assembly system from the design perspective, considering the entire assembly system. The questions that will be answered are related to:

1) What is new in smart assembly compared to previous research areas such as design for assembly (DfA), product platforming, and lean manufacturing?

2) What are the key elements of a smart assembly system?
3) How should the challenge of smart assembly be undertaken?

Section 2 of this paper contrasts the current definition of smart assembly with previous research areas and focuses on the associated challenges. Section 3 describes critical elements of a smart assembly system. Section 4 proposes a general roadmap for motivating and attacking the challenge of smart assembly. Section 5 draws conclusions based on the proposed approach.

2. SMART ASSEMBLY AND THE STATE OF THE ART

Product design has been influenced by several research topics in the last decade, many centered on the integration of design and manufacturing considerations. To determine the novelty of the concept of smart assembly among other design concepts, a short review of some related research is presented. The topics to be discussed include design for assembly, product modularity, and virtual simulations from a product design perspective, and lean manufacturing from a process design perspective.

1.1 Design for Assembly

Design for assembly methodologies has been popular for a couple of decades [1]. These methods are usually used to evaluate assembly designs in terms of functionality, ease of assembly, and number of assembly components. Unfortunately, many times this methodology is applied too late in the design process resulting in difficulties to implement the desired changes. DFA common stages are:

- functional analysis;
- manufacturing analysis;
- material handling analysis; and
- assembly analysis [2].

The functional analysis stage focuses on determining when components do not perform any major function in the designed product and are thus candidates for elimination or combination. Manufacturing analysis considers the materials and manufacturing processes to be used during the assembly process with the goal of reducing the number of assembly steps and identifying opportunities to reduce process steps and the variety of materials. The objective of material handling analysis is to study how the components are handled during the assembly process and eliminate orientation and insertion problems during the assembly. Finally, the assembly analysis stage reviews the assembly sequencing and planning as well as tooling usage. In general, these methodologies identify design issues, but do not necessarily provide re-design solutions.

Smart assembly clearly must consider the key elements of DfA; however, its main focus is on the integration of the process design into the product design. Integrating assembly products and assembly systems design have been proposed for multi-product systems [3] and well as for product families [4]. Both efforts concentrate in including during the product design the implications of the design decisions in the assembly process. In contrast, the concept of smart assembly is defined by the process used to put together the individual components in a product, instead of the product itself. Therefore, the design process concentrates in how to design the best generic assembly process, and starting from there, design the product. As mentioned earlier, DfA is a good tool to evaluate a design [5], but not to determine a design alternative and is even less effective to design the assembly process.

1.2 Product Modularity

In the last two decades, product design has been strongly influenced by mass customization requirements. The main challenges are how to maintain efficiency and low cost, while increasing variability. As a response to these challenges, many companies are using product modularity and product platforming during their design processes [6]. These challenges are very significant during the design of assembled products, where many different subassemblies interact. Defining product modules requires the identification of product functional requirements, and mapping these functional requirements to product physical characteristics that can define individual components. Finally, interface constraints must be identified for each module [7]. In terms of designing product platforms, two approaches are commonly used 1) a top-down approach, and 2) a bottom-up approach [8]. The top-down approach consists on developing different product derivatives based on one product platform. On the other hand, the bottom-up approach focuses on identifying consolidation opportunities for communization in a family of existing products.

Product modularity research has concentrated in how to systematically identify product modules during the design process. Modularity describes the degree to which different assembly elements can be aggregated/integrated as a sub-assembly or disaggregated. Several methods have been proposed for this purpose, each using different techniques such as heuristics [9], Quality Function Development [10], optimization-based [11], variant design [12]. Guo and Gershenson [13] present a comparison of different modularization methods in the context of product architecture. Schilling [14] presents a general theory for modular systems based on causal models from studying engineering and non-engineering systems.

In the case of modularity, some attempts have been seen in working with process modularity as well as integrating it into product platforming. Particularly, the assembly process work by Lai and Gershenson [15]. Bryan et al. [16] proposed the concept of co-evolution to integrate the development and design of product families with the assembly processes. The intention of the smart assembly methodology will be to exploit the advantages of modularity in designing key basic assembly operations. It should be pointed out that that the concepts of modularity and platforming need to be applied to both the product and the process concurrently. Then, a single process module can be used and reused for different products.

1.3 Lean Manufacturing

Another relevant aspect to be considered in a smart assembly system is the manufacturing processes related to bring each component together. In this direction, a smart assembly considers a process in which each production activity adds value to the overall system. This is very similar to the lean manufacturing philosophies introduced by Toyota around 1950 [17] and being implement worldwide. Lean manufacturing aims for the continuous elimination of wastes and emphasizes the reduction of time and resources usage during the fabrication of a product [18]. Lean manufacturing is a multi-dimensional effort that considers a wide variety of manufacturing practices. Among the principles generally associated with lean manufacturing are – bottleneck removal, cellular manufacturing, continuous improvement, cycle time reduction, just-in-time manufacturing, pull/*kanban* systems, and total quality management [19]. It should be noted that most of the academic effort around lean manufacturing can be found on the implementation of these practices or that adaptation of these practices to non-manufacturing processes more than in basic research.

While designing an assembly process, the lean manufacturing philosophies are a good starting point but are limited by the complexity of integrated product and process design. Lean can be used to identify non-value added activities, but it cannot design the process itself. Smart assembly design has to incorporate the interaction between the process, the human operator, and new technologies. To accomplish that, it will be necessary to look at everything that is of value within the assembly operations and apply the methods of waste elimination, flow, pull, just-in-time, and continuous improvement.

1.4 Virtual Reality Tools and Assembly Simulation

Computer simulation tools are becoming a key component of the product development process in manufacturing industries and a common strategy during the design process. Simulation is also used for verification of assembly and maintenance operations [20]. To these ends, virtual reality (VR) is also being used during the design process, where assembly simulation is one of the most challenging applications [21]. The major problem is that assembly processes include high levels of interactions among parts, tools, and human operators. Immersive VR can be used for formalizing the design process, including learning from assembly process patterns within a virtual environment [22]. The continuous decrease in the cost of VR technologies will soon make them available to more manufacturing industries as well. This will allow to making possible to conduct assembly design analysis, planning, and motion studies in a virtual world. In addition, VR is rapidly moving to become a key training tool in manufacturing environments, allowing operators to learn assembly operations. An example of these applications is the development of the Virtual Training Studio [23]. The fast development of new virtual tools is transforming the way that assembly systems will be designed and built.

As expressed by Dr. Tilove in his definition of smart assembly, the use of virtual simulations plays a fundamental role in designing new process. The biggest improvement opportunities in productivity and agility during the designing process of new assembly operations rely on the ability to smoothly integrate real and virtual environments. Virtual reality tools may provide a fast and reliable alternative to evaluate and validate different design alternatives as well as new technologies and may prove to be a key technology for maintaining cost, quality, and delivery while new technologies are implemented.

3 SMART ASSEMBLY

As mentioned in the Introduction, smart assembly is defined as the integration of different product design and manufacturing elements to increase the productivity of assembly systems. However, this definition is rather vague. It should be probably better defined by how will a designer know when he has achieved it or what does he need to do to achieve it. The next logical question is how to achieve Smart Assembly. This initial roadmap for achieving Smart Assembly is presented based upon both what is needed to achieve it and how the authors think that these achievements can begin to happen. The goal of the roadmap is to excite people in tackling this grand challenge and to get people to group together to tackle the challenge in an organized and concerted effort.

Let's begin with the issue of what is Smart Assembly. Again, this is a starting point for this journey towards achieving this grand challenge. The purpose is to begin this discussion by creating this initial straw man of the elements of Smart Assembly. The elements of smart assembly have been separated based on what goes on in an assembly plant, five elements have been identified: product; people; processes, equipment, and tools; information; and technology (Figure 1). Within each of these elements, the goal of this paper is to take a high level view of what are the key changes to these elements in Smart Assembly.

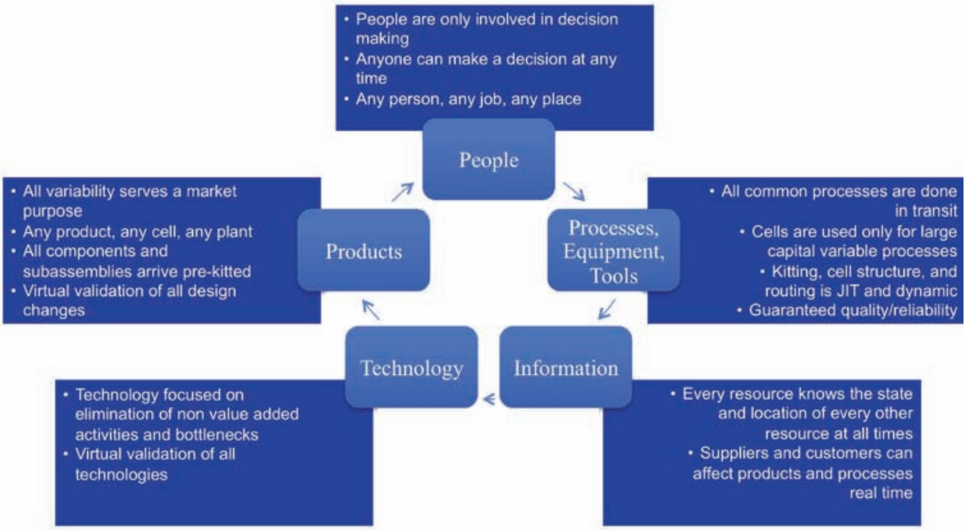

Figure 1. The Five Basic Elements of Smart Assembly

3.1 Products Element

The first question is not what type of products, but how does the product interact with the assembly process in a Smart Assembly environment and how is a plant developed for a Smart Assembly environment. There are three key points when it comes to how a product is developed under this environment: 1) any product, any cell, any plant; 2) all components and subassemblies arrive to the assembly station pre-kitted; and 3) virtual validation is used for all design changes.

Product and process, as well as equipment and infrastructure must be developed concurrently to give the utmost possible flexibility. Since this paper is about the grand challenge, it will discuss the optimum level for each of the key points. Any assembly cell or system within any assembly plant should be capable of assembling any product within a product family. For this to happen, the integration of product and process development is required. The assembly processes and plants must be developed with the range of products in mind. The products themselves must also be developed with appropriate commonality of components and necessary assembly processes to allow for this flexibility. The goal is flexibility, allowing just-in-time adjustments to product volumes and cell assignments. A particular product destined for (customized for) a particular customer could be assembled in the location closest to that customer or in the plant that is best for that particular product based upon current production volume and capacity, even based upon current work stoppages. The result is the flexibility to plan the assembly process for the highest quality, quickest delivery, and lowest cost.

Pre-kitting is another key technology for enabling flexibility and increasing throughput. In kitting, all components to be assembled to a system are typically grouped to move in unison to the point of assembly. The concept of pre-kitting expands upon this, to include all tooling and equipment. Tooling and equipment would move with the components to the point of assembly. This allows for the flow of non-common tooling and equipment (used for only particular products within a product family) along with the product; flow being one of the central elements of lean manufacturing. This flow allows for the just-in-time routing or re-routing of product through the plant, it also allows for the use of “bare bones” assembly cells that are designed to do any job with the use and frequent change of product-specific tooling where necessary.

Products must be developed quickly, and when developed they must perform as expected with respect to the assembly process. This requires an integrated approach to the design of products and processes. To promote and enable integrated product and process development, and to enable the quick changeover to new products and product families, it is necessary to validate the assembly process for the product prior to production. The best way to do this is to use such validation as part of the integrated design process, necessitating virtual validation. The virtual simulation of the assembly process must be accurate enough to “guarantee” that the product and process are ready for production without any production trials. Virtual validation should be used for all product changes and all process changes as well as for new products and processes.

3.2 People Element

People are what make a plant run, no matter how automated the plant. In particular, people (well trained people) have superior abilities to reason in some situations. Of course, people can be less efficient and less precise than automated counterparts in many situations as well. Therefore, it is fundamental to use this fairly expensive resource, people, where it has the most value. People should be used for efficient and flexible decision making. To achieve this, it is necessary that: 1) people are only involved in decision making; 2) anyone can make a decision at any time; and 3) any person, any job, any place.

To achieve cost, quality, and delivery resources should be used at the jobs they do best. Compared to other available resources, people excel at qualitative decision making and personnel management. It is important then to design the tasks within a Smart Assembly plant so that people are not relied on for repetitive tasks, quantitative analysis, or other tasks that are better done by automated resources. There are many tasks, including continuous improvement analysis, that require human resources. Keep in mind that no job or task involves non-stop qualitative analysis or management; however, people should only be involved in those tasks that require such work as part of the job.

If a plant has people doing tasks that involve qualitative decision making, it would be inefficient to not allow them to have the authority to make or implement that decision. Therefore, any person confronted with a situation in which they are faced with a decision to make as well as access to the information upon which to make that decision, they must be empowered to make that decision and to implement that decision. That being said, every person should have access to all information at their fingertips as we will discuss later, so every person should be empowered to make any decision.

Similarly, if a person finds him/herself in a position where a task needs to be done, they should have the skills to perform that job at the time and place it is needed. In a Smart Assembly plant, this enables the fastest possible throughput.

3.3 Processes, Equipment, and Tools Element

Processes, equipment, and tools are the most visible and often most expensive parts of an assembly plant. These resources also have as much impact on cost, quality, and delivery as do raw materials and work in process. Therefore, processes, equipment, and tools should flow through a plant in a similar manner. In a Smart Assembly plant, these resources should be subject to:

- all common processes are done in transit;
- cells are used only for large capital variable processes;
- kitting, cell structure, and routing is JIT and dynamic; and
- guaranteed quality/reliability.

One dramatic difference in the envisioned Smart Assembly is the use of AGVs as common and frequent transit resources. While the structure of cells will be dynamic and flexible, and therefore should be located in an efficient layout, there will probably still be a need for longer distance transit. Typically, such transit has been completely non-value added. A Smart Assembly plant should try to get value out of that process by doing assembly operations while materials are in process. This paradigm can be used for the kitting as well as the main assembly operations. By going beyond this paradigm to make in transit assembly a planned and advantageous part of the assembly processes, there is more to gain in terms of cost, quality, and delivery. However, to make this cost effective with respect to the development and production of the AGV technology (as described in the technology section) and to insure that the technology is being used efficiently, only assembly operations that are common across the product family should be performed on the AGVs. Processes that are unique to a particular product, those that require precision, those that require expensive or complex tooling, and those that require specific environmental conditions are better done in a cell.

By making use of flexible cells and full kitting as discussed in earlier sections, as well as the in-transit processing described in this section, it is possible to have JIT dynamic assignment of in plant resources. This JIT assignment includes planning for kitting contents and movement, cell structures and location, all material and resource routing, and even human resource assignments. This enables the Smart Assembly plant to adjust JIT to changes in demand, resource availability, and capacity based on data not only from a line or plant, but on data from throughout the enterprise and the supply chain.

The last piece to this puzzle is, to some degree, the elusive goal of manufacturing. Smart Assembly cannot be at the mercy of product quality and resource reliability. As stated earlier, the purpose of this paper is to set the scope of what it Smart Assembly, the next step is for those in academia, industry, and the government to develop the technologies and processes to make Smart Assembly a reality. There is still a lot of work to do in the realms of quality and reliability.

3.4 Information Element

Information clearly plays a central role in Smart Assembly. Information like materials and resources is precious. The cost, quality, and delivery of information must be respected just as it is for materials or equipment. Therefore, we need to make sure that the flow of information is flexible and occurs JIT. Such an enterprise-wide paradigm is not easy to achieve, but the benefits are significant and good work already exists towards making this a reality [24]. The two key components of information in Smart Assembly are: 1) every resource knows the state and location of every other resource at all times; and 2) suppliers and customers can affect products and processes.

The first piece in the information puzzle is that state of knowledge of the enterprise. If every resource knows the state and location of every other resource at all times, they are in a state of "perfect knowledge." Resources include materials, processes, equipment, tooling, cells, and people. These resources should extend up and down the supply chain as we discuss in the next point. This state of perfect knowledge will enable the decision making, dynamic nature, and JIT flexibility that has been discussed so much in this paper. The speed and accuracy of the flow of information is central to this paradigm.

Given this state perfect knowledge and this ability for dynamic and JIT decision making, the capability of such decisions can extend beyond the plant boundaries. For true JIT flexibility, suppliers and customers must be able to affect products and processes as well. Their input to the state of knowledge will influence dynamic routing and planning. In some cases, customers and suppliers should have the capability to make decisions as well. Customers should be able to know the current state of all of their products, and any attributes of that product, including volumes and delivery dates, which they can still impact. Customers would then be able to impact their current and future orders real time. Suppliers would have similar control. They would be able to input changes in their capabilities to better inform delivery dates and capacity. Again, such information would then be used to impact routing and planning in the plant and make any necessary changes to the supply chain.

3.5 Technology Element

Technology, and the development of new technologies, will be an important part of achieving Smart Assembly. As with the other elements, this development should yield technologies with a particular characteristic that is uniquely that of Smart Assembly. While technologies can be used for a whole host of activities, it is important to focus this development on those that truly impact cost, quality, and delivery in the long term, and as well to make sure that the implementation of such technologies does not hamper cost, quality, and delivery in the short term.

Again, there are many things that technology can do. Just because there is a possibility of a new technology, does not mean that it should be pursued. The key is to prioritize the pursuit of those technologies that actually impact the system in the strongest manner first. To this end, it is important that any new technology be focused on the elimination of non-value added activities and bottlenecks within the system. As per the Theory of Constraints, it is at these bottlenecks only that we can improve the throughput of the system, and as per lean manufacturing, it is these non-value added activities that are costing us the most and need to be eliminated.

As with product and process changes, it is important that the introduction of these technologies not hamper the actual production in any way. To accomplish this, the technology must first be implemented off-line. In Smart Assembly, this is best achieved through virtual validation. We must have the capability to have an up to date, dynamic model of the supply chain that can be used for simulation and virtual validation of every change in the enterprise – both for implementation and for decision making.

4 SMART ASSEMBLY ROADMAP

As a secondary part of this paper, we hope to set a short term timeline for motivating Smart Assembly work in both academia and industry (with government and NGO collaboration). We hope that, over the next two to three years we will be able to delineate the scope and the enablers of Smart Assembly as well as use that information to organize a larger scale assault on the challenge. To this end, we show here a five step plan: identify roadblocks, identify enablers, enabler solutions, smart assembly integration visualization, and define the future.

Figure 2. Smart Assembly Roadmap

4.1 Identify Roadblocks

The first step in this short term roadmap is to better understand why Smart Assembly does not already exist. This will require a good understanding of the state of the art in each of the elements described earlier in this paper: products; people; process, equipment, and tooling; information; technology; and probably also supply chain. Based upon the gap between the state of the art and the necessary elements, it is then necessary to understand the relative size of this gap. However, more important than the size of the gap is the identification of any roadblocks that may stand in the way of these achievements. Roadblocks will be analyzed in two dimensions for each of the elements. First, they will be analyzed from the product, process, and systems viewpoint. Second, the roadblocks will be studied with respect to their impacts on cost, quality, and delivery. The goal is to prioritize the roadblocks by what they will take to solve them and also by the impact that the solution will have on Smart Assembly operations.

A study of the roadblocks can be easily undertaken by a small group of academics with good industry contacts. It is best to split up this work so that many industry sectors and many academic backgrounds are included. At the end of the activity, it would be necessary to report out for comment at a workshop.

4.2 Identify Enablers

Given the identified roadblocks from the first task, the next step would be to determine ways in which the roadblocks can be overcome. We use the term enablers to describe the scoping of these solutions. It is important to understand at this point the objective of this step is to scope out the enabling solutions, to define the problem of finding the solutions. Based upon our discussions of the elements of Smart Assemblies, enablers will come in several general classes:

- technologies;
- methods / frameworks;
- product characteristics;
- process constraints; and
- visualization capabilities.

The process of identifying the problems and scoping the enablers will once again be multi-institutional. Those who have taken to the paradigm of Smart Assembly and those who are well versed in each of the pertinent elements and their roadblocks should be well positioned to undertake such work. At some part, there must be a comparison of notes among those involved so that the scopes of the enablers come together to cover the Smart Assembly paradigm. The end result will be a smaller set of challenges within each of the elements, ones that are easily digested and understood as individual, solvable problems; ones that can later be put in concert with each other.

4.3 Enabler Solutions

Clearly, the next step is then to work on the given problems to develop the enabling solutions. People will develop a smart assembly integrated architecture, develop smart assembly technologies, develop smart assembly methodologies, and develop an integrated visualization environment for smart assembly. At first, within the short term, it may be best to work on solutions that work for specific applications, therefore necessitating a close link with industry. We believe that it may take several such applications within each enabling problem before the process of generalizing such solutions into widely applicable technologies can proceed. Ideally, we would love to see researchers collaborating on a single application so that the entire vision of Smart Assembly can be shown for others to adopt and adapt. The longer range goal of generalized solutions is not close, and will rely on the building of a Smart Assembly community to disseminate the short term advances.

4.4 Visualization Integration

Based upon this notion of a community working on a singular application in the short term, we propose a culminating virtual visualization of Smart Assembly; a virtual implementation of integrated architectures with smart assembly technologies and methodologies. Such a virtual validation of the smart assembly paradigm will serve as both a demonstration and validation of this initial research as well as a baseline for comparison in future smart assembly research. The wide, free dissemination of the visualization components is essential for the future success of this field.

This visualization should be undertaken by those parties that are developing the visualization capabilities. They will work together with the developers of the enabling solutions to make sure that the solutions are integrated properly (most likely an iterative process that will yield solution improvements and visualization improvements). Once incorporated, the visualization should be run and cost, quality, and delivery metrics should recorded. If done properly, these should be compared to a baseline assembly environment. These results need then be broken down to understand the results at the overall application level, as well as at the level of impacts of each of the solutions. This data will be used as the driving force for improvement of the solutions as well as a motivation for the generalization of the solutions.

5 CONCLUSIONS

In this paper, the concept of smart assembly is introduced and discussed. Smart assembly seeks to transform the way in which products are designed and assembled by using virtual and real time assembly methods to significantly reduce non-value added activities and speed the response to change. As in most manufacturing environments, the key elements identified in a smart assembly environment are people, product, process, technology, and information. The key components of each of these elements include, 1) flexibility in product assembly, 2) JIT kitting, 3) virtual validation, 4) people as decision makers, 5) flexible personnel, 6) processes done in transit, 7) cells for large capital variable processes, 8) JIT production planning, 9) guaranteed quality/reliability, 10) resource awareness, 11) suppliers/customers empowerment, and 12) technology focused on the elimination of bottlenecks.

A secondary part of this paper is the presentation of a roadmap for the development of the smart assembly vision. This five step plan - identify roadblocks, identify enablers, enabler solutions, smart assembly integration visualization, and define the future - considers the need to identify current roadblocks and the corresponding enablers that will allow to making the presented vision into a reality in the short term. This includes the need to develop smart assembly testbed in different scenarios to motivate others to follow this direction. This testbed will be used for validating the various technologies, methods / frameworks, product characteristics, process constraints, and visualization capabilities of Smart Assembly.

Finally, it should be pointed out that the main goal of this paper is to motivate Smart Assembly work across multiple researchers and practitioners including both academia and industry.

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