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## MxD FINAL REPORT PROJECT 21-06-01

| Scheduling for Manufacturing Applications in Real-Time (SMART) |                                                                                                                 |
|----------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|
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## I. EXECUTIVE SUMMARY

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Efficient scheduling can increase the productivity of a shop floor without large investments in new hardware. Thus, it is a potentially simple way of improving the competitiveness of manufactures, especially in high-wage countries like the US.

However, the obstacles to investing in scheduling technology, especially for small- and medium sized manufacturers, are the high cost of system integration without an upfront guarantee as to how much the productivity will increase.

The SMART project developed and demonstrated an optimization based online scheduling framework at the shop floors of Triangle Package Machinery and the ICAMS lab of Auburn University. In both cases online scheduling has successfully been applied to the shop floor in closed-loop operation. Furthermore, the project developed an order sequencing tool for a telehandler assembly line of JLG. Although this solution could not be demonstrated in an online operation on the shop floor it was investigated with a discrete event simulation of the shop floor. The simulation indicated a productivity increase of more than 12% that was achieved through the prioritization of orders based on their material availability.

To ensure the knowledge transfer to other practitioners of scheduling and engineering students, a Landscape Assessment and a Guidebook for best practices have been compiled out of the project's results. Additionally, a detailed case study documents the findings of the JLG use case.



## II. PROJECT DELIVERABLES

The following list includes all deliverables created through this project. These deliverables will be referenced throughout this report and should be accessible on the MxD membership portal in accordance with the rights defined by the Membership Agreement. Specific deliverable types include, but are not limited to, the following items.

- *Software modules*
- *User guides/ developer documentation*
- *Demos/case studies*

Table 1: SMART Project Deliverables

| #  | DELIVERABLE NAME                            | DESCRIPTION                                                                                                                                   | FORMAT OF DELIVERY                                  |
|----|---------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|
| 1  | Landscape Assessment                        | Asset audit of enterprise systems, data collection mechanisms (e.g. sensors), and define baseline KPIs, metrics                               | .pdf                                                |
| 2  | Data Architecture and Integration Framework | Documentation of the data architecture and integration framework including approach, diagrams, and considerations for compliance and security | .pdf                                                |
| 3  | Implementation at Large Manufacturer        | Executable of Siemens prioritization tool for JLG                                                                                             | Zip folder with .exe file, readme, licensing.txt    |
| 4  | Implementation at SMM Manufacturer          | Docker container of the Siemens scheduling solution for Triangle's manufacturing site                                                         | Docker Image (.tar.gz File) and Readme              |
| 5  | Discrete Event Simulation Model             | JLG Skytrak assembly line built on the Siemens Tecnomatix modeling software                                                                   | Simulation model (.spp File)                        |
| 6  | Guidebook                                   | A general guidebook detailing best practices for choosing a scheduling solution and common pitfalls to avoid                                  | Zip folder with .exe file, readme, and example data |
| 7  | Detailed Case Study                         | Simulation study that illustrates the application of the prioritization tool within the JLG model, utilizing real-world data.                 | .pdf report and .xlsx simulation data               |
| 8  | Technical Demonstrations at MxD             | Presentation of technical research and development outcomes in MxD meeting                                                                    | .pptx                                               |
| 9  | Software: Online Scheduler                  | Executable version of the scheduling software                                                                                                 | .exe file with readme and example data              |
| 10 | Developer Documentation                     | Includes software documentation, integration documentation, documentation for modifications to software                                       | .docx                                               |
| 11 | Technology Transition Workshop              | Workshop for MxD members on scheduling technology and possible applications at the ICAMS Lab                                                  | URL to Demo Video                                   |



### III. PROJECT REVIEW

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Workstations on the shop floor are becoming more capable, connected, and intelligent. These advances improve flexibility and productivity on the individual machine level. However, the potential of an optimized and flexible task assignment among the different workstations remains largely untapped by many manufacturers.

One obstacle to the use of advanced scheduling technology is the Engineering and IT effort required to integrate and adopt a scheduling solution on the shop floor. Without customization, any scheduling software can only provide coarse schedules which often require manual post-processing before they can be applied; thus, their benefit is limited. The customization step ensures a good schedule quality but is very costly. This deters especially low-volume manufacturers from investing in advanced scheduling technology. Consequently, products are still queuing up in front of one workstation, while other workstations sit idle.

#### Use Cases & Problem Statement

Manufacturing scheduling is the process of planning the sequence of production tasks and activities in a manufacturing facility. It aims to optimize the use of resources such as machinery, labor, and materials while meeting production targets and deadlines.

Scheduling research is usually focused on Job-Shop problems or Flow-shop problems. These scheduling problems provide generic constraints but often do not represent the specific constraints and rules of a real-world shop floor. Hence, the resulting schedules are generally too coarse, do not achieve good resource utilization, and sometimes are not even executable on real shop floors.

Furthermore, optimization-based approaches for these problems suffer from the combinatorial explosion of possible schedules. Fast solutions are usually far off from the optimum, whereas finding the true optimum might be computationally intractable. On the other hand, a long-term schedule is often rendered void by delays and other deviations from the plan, that happen during the execution of the schedule.

Custom-made scheduling solutions for industrial applications can deliver very good schedules - depending on the expertise of the integrator. However, these tailored solutions are very costly and often have a limited transferability from one shop floor to another.

Following the industrial user perspective, the following problem statements are addressed:

1. "As a production supervisor, I want to have a feasible production schedule for my shop floor at any time so that I can deliver on time and reduce unnecessary idle times on my workstations."
2. "As a production manager, I want to know upfront if said scheduling solution will yield a positive return on invest for my shop floor."
3. "As a production manager, I want to use the solution from the MxD membership use case for my shop floor without paying for a huge engineering/adaptation effort."

#### Scope & Objectives

One solution to overcome the dilemma between large computation times for scheduling optimization and the required flexibility to quickly react to deviations happening on the shop floor



is to use a closed-loop approach, in which the scheduler is constantly updating the schedule based on the latest status information, but only for a limited look-ahead time. This is the idea of online scheduling.

The scope of the SMART project is to demonstrate online scheduling for several use-cases:

- Demonstration of the ICAMS Lab of Auburn University. This use-case resembles the traditional job-shop problem.
- Demonstration at Triangle Package Machinery. This use-case is a real-world shop floor, at a SMM.
- Demonstration at the JLG Skytrak assembly line. This use-case is a flow-shop example at a large manufacturing line.

Beyond the mere demonstration of the applicability of online scheduling, the SMART project also evaluates the economic benefits of such a tool. By means of a back-to-back discrete simulation of the shop floor, the project did a before-and-after comparison of the shop floor with and without online scheduling applied.

Last but not least, the SMART project provides an overview of scheduling technologies that are used in the industry and a set of best practices and guidelines that have been gathered during the execution of the SMART project.

### **Planned Benefits**

Advanced scheduling can increase the competitiveness of US manufacturers even in labor-intensive brownfield production environments. The immediate benefit of the SMART project is the demonstration of potential savings that can be achieved through online scheduling. Through the corresponding landscape assessment and guidebook this should enable other manufacturers to evaluate the online scheduling technology for themselves. The latter documents will also enable other scheduling practitioners and students to learn from this example and foster a wider application of this technology.

On the 2–5-year horizon, Siemens plans to continue the development of the online scheduling technology and provide a commercial offering for manufacturers. Compared to the current practice of customized scheduling solutions this scheduling framework will help to reduce the initial investment to set up an optimization-based scheduling solution on a shop floor and thus enable more manufacturers to use this technology.

## IV. TECHNICAL APPROACH

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The overall task of the project is to demonstrate the benefits of online scheduling and provide guidance on how to apply this technology for manufacturers across different industries. To this end, the tasks of this project can be categorized into three different workstreams:

- a) The technical demonstration of online scheduling at JLG, Triangle Package Machinery and the ICAMS lab. This task includes the implementation of the online scheduling software and the integration of that software to the respective shop floors.
- b) The Return-of-Invest investigation for the JLG use-case. This task includes the creation of a discrete-event simulation model of the Skytrak assembly line at JLG and the before-and-after comparison of the line with and without online scheduling.
- c) The knowledge transfer to other manufacturers and engineering students. This task includes the compilation of a landscape assessment of scheduling technologies and a Guidebook with best-practices and learnings from the SMART project.

The following sections describe the work and the technical approaches to these three tasks in more detail.

### Technical Demonstration of Online Scheduling

#### Data Architecture & Integration Framework

Production scheduling in general requires information about the workstations that are available on the shop floor as well as information about the tasks that should be processed. In addition, online scheduling requires information about the progress of ongoing production steps to keep the schedule up to date and monitor for possible delays that might require an adaptation of the current schedule.

The first step for the technical demonstrations was therefore planning the data architecture and system integration, i.e. how information about workstations, production orders and their corresponding workplans is getting from the shop floor to the online scheduling software.

A key principle for the maintenance of shop floor data is to avoid duplication of data sources. The information about the equipment and status on the shop floor as well as the production orders should only be maintained in one location respectively and synchronized to all other programs that require this information.

In a production environment, these data sources are typically an ERP and/or MES. The online scheduling software will acquire its data from these sources. However, some details that are required for the generation of a schedule might not be modeled in these central data sources and need to be provided separately. Examples for such details are information about the rules for setup-operations or whether a task must be completed in a single shift or can be resumed after a break.

The details and results of this task are documented in the Data Architecture & Integration framework, which is provided as a deliverable of the SMART project.

#### Integration at Triangle Package Machinery

One use-case is the manufacturing site for food packaging machines at Triangle Package Machinery in Chicago, IL. The only scheduling was applied to the component manufacturing

part of the shop floor, which comprises 33 machines, both CNC and manually controlled and 29 manual workstations.

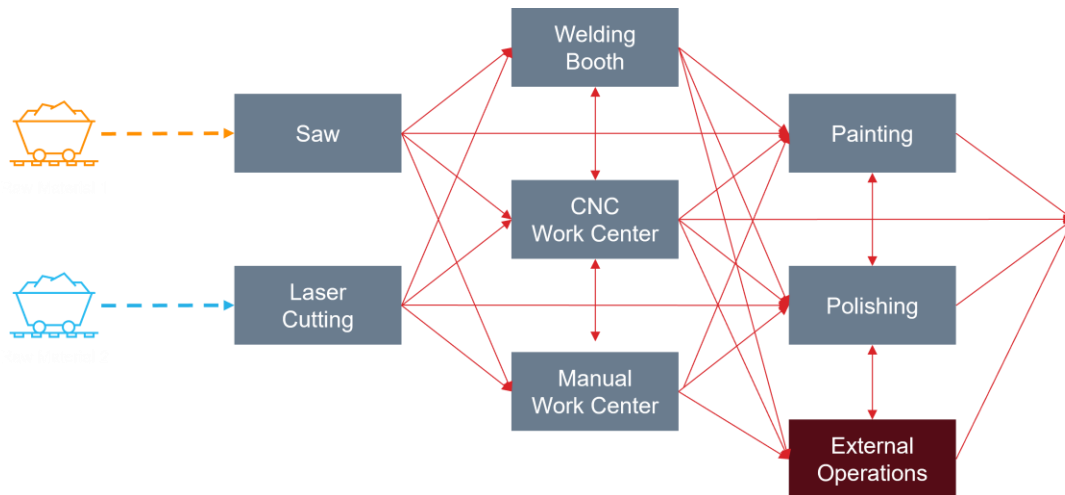


Figure 1: Work Order Routing Possibilities at Triangle Package Machinery

Figure 1 shows the possible routings for individual orders on the shop floor. The component manufacturing can be generally described as job-shop manufacturing, but with additional constraints that had to be included in the scheduling model. The two most notable deviations from the pure job-shop model are setup times that must be considered on machines – depending on the previous order. And the second constraint is a grouping constraint, which allows several jobs to be executed simultaneously on a workstation if the required raw material for these jobs is the same.

As engineering interface and for the shop floor connectivity, the SMART project used the established offline-scheduling software from Siemens, Opcenter APS. The system architecture for the Triangle use-case is depicted in Figure 2.

The above-mentioned constraints have been modelled in Opcenter and have also been implemented into the optimization framework. Furthermore, a generic REST interface between Opcenter and the optimization framework has been developed that allows to the online scheduler to receive all relevant resources, tasks, and constraints for the scheduling task from Opcenter via in a standardized format. This interface does not depend on the use-case at hand but can be reused for other use-cases as well – in fact it has been reused for the ICAMS use-case even within the SMART project.

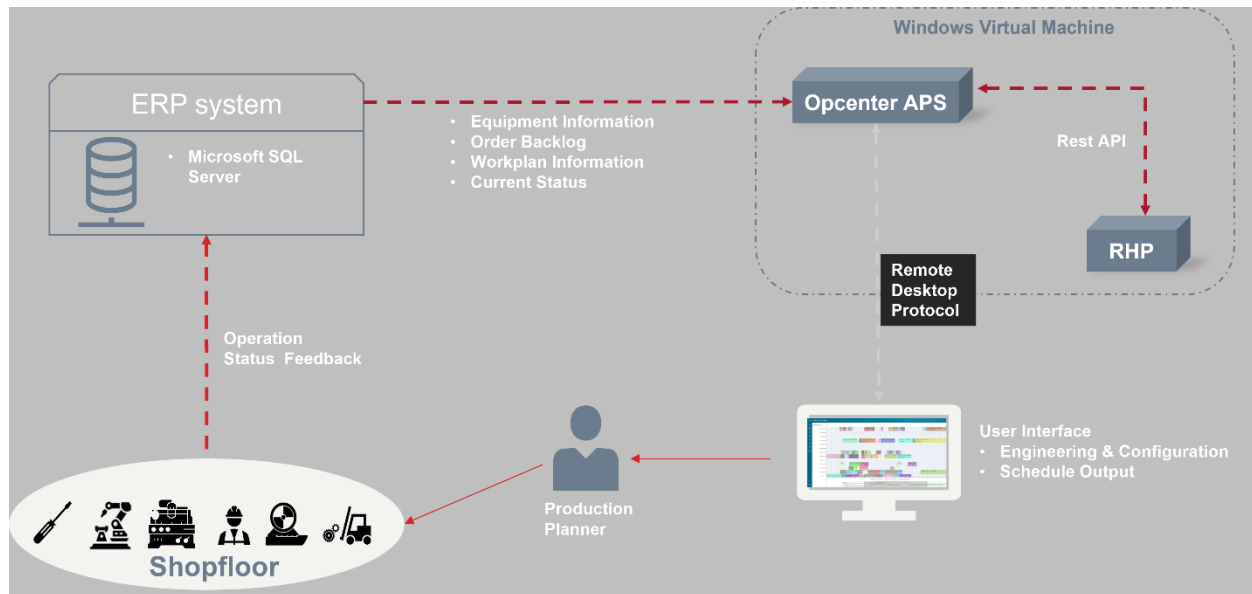


Figure 2: System Architecture for Triangle Package Machinery

### Integration at the ICAMS Lab of Auburn University

The Interdisciplinary Center for Advanced Manufacturing Systems (ICAMS) at Auburn University focuses on advancing manufacturing technology and education. The lab supports small and medium-sized manufacturers by offering resources and training for Industry 4.0 technologies and smart manufacturing.

The online scheduling use case at ICAMS consists of three workstations and a classic job-shop production. The system architecture is very similar to the Triangle setup, the main difference being that the ICAMS lab did not have an ERP system, but the production data was stored and edited in a MySQL database directly. This database included fields such as product codes, material types, cycle times, and machine condition. Live data updates enabled the optimizer to adjust schedules in response to changes like early/late job completions or new order arrivals. Here, the database communicated with the shop floor to receive updates on operations via computer screens visible to the operators.

## Scheduling Optimization for Job-Shop-like problems

Both the Triangle use-case as well as the ICAMS use-case are job-shop problems, albeit with additional constraints – as in the Triangle case. The optimization for shortest makespan of a job-shop schedule is an NP-hard problem. The number of possible combinations grows exponentially with the number of manufacturing tasks and therefore prohibits the full enumeration of all possible schedules for most real-world problems.

The approach to compute the schedule used in the SMART project is a combination of Branch-and-Bound optimization and heuristics. By limiting the planning depth of the schedule and using a heuristic to estimate the cost of the remaining tasks, we calculate the best succeeding actions within a very short time. An example of a tree search with a limited planning depth of two steps is shown in Figure 3.

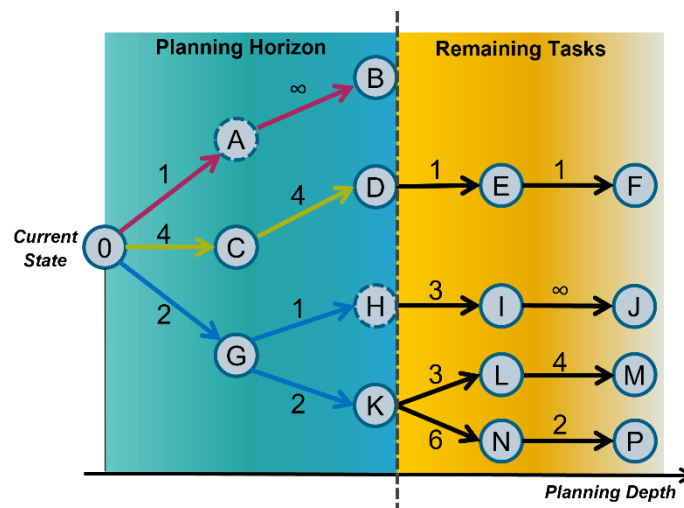


Figure 3: Tree Search with limited planning depth

Only the first two consecutive actions are enumerated in each branch (blue background). The remaining tasks (yellow background) are considered by a heuristic that estimates the cost of execution. The cost at each node is the sum of the accumulated cost to reach this state and a lower bound estimate of the remaining cost to complete the schedule. This allows the algorithm to prune branches early and ensures an unbiased comparison between different states of the same generation. The latter feature is important to decide which of the partial schedules is the best option.

We use a depth-first scheme for the exploration of the tree in the planning horizon. This immediately provides a feasible solution and a good lower bound cost estimate for the enumeration of the other branches in the planning horizon. The philosophy behind this search method is, that we first look for a feasible solution and use the remaining time in the planning cycle to look for better options.

For efficient branching we use active schedule heuristics. It is important to note that the heuristics used in this algorithm, both for branching and for the lower bound estimation, are

applicable for manufacturing scheduling in general and are not use-case specific. Therefore, we do not need to adapt the optimization algorithm depending on the use-case.

From this optimization we get the best set of actions for the limited planning horizon. This is not necessarily the global optimum which considers all production tasks. However, for a sufficiently large planning depth, this will be a good approximation of the true optimum.

### Integration at the JLG Assembly Line

In contrast to the other use-cases, the JLG assembly line is not a job-shop problem but rather a flow-shop problem, i.e. orders are processed in the same order by the same workstations. Figure 4 shows the major stations of the assembly line for the Skytrak telehandler.

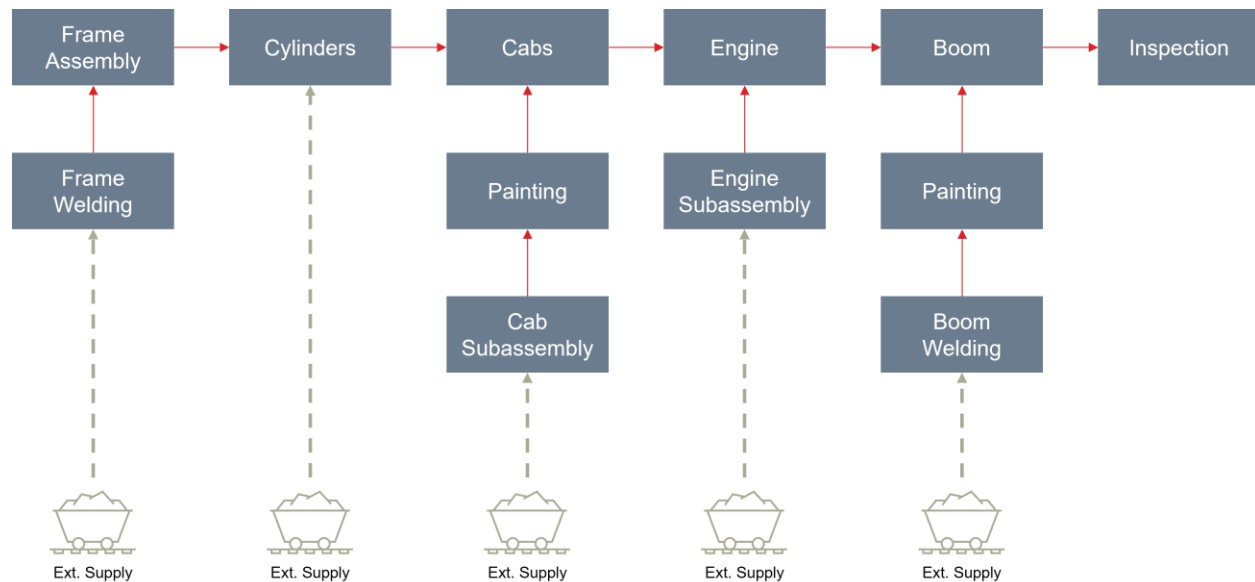


Figure 4: JLG assembly line

The major challenge for this type of production is not the assignment of orders to their workstations but the coordination of the various sub-assemblies to the final assembly line. The Skytrak telehandlers that are manufactured can be individually configured by the customer. So, for each order moving along the final assembly, the right parts have to be at the right station in time. The sub-assemblies have varying lead-times. The decision which orders to start next for the frame-subassembly – the one with the longest lead-time – determines the sequence of orders for the other sub-assemblies. However, at the time when the decision for the next frame is made, not all other sub-assemblies might have the required material available to build.

Choosing the assembly of a frame that cannot be fully assembled by the time it reaches the final assembly mean leads to unnecessary rework to finish partially completed orders. The SMART project developed a prioritization tool, which provides suggestions on the next frame to start in the sub-assembly, based on the inventory and the information about the pending orders.

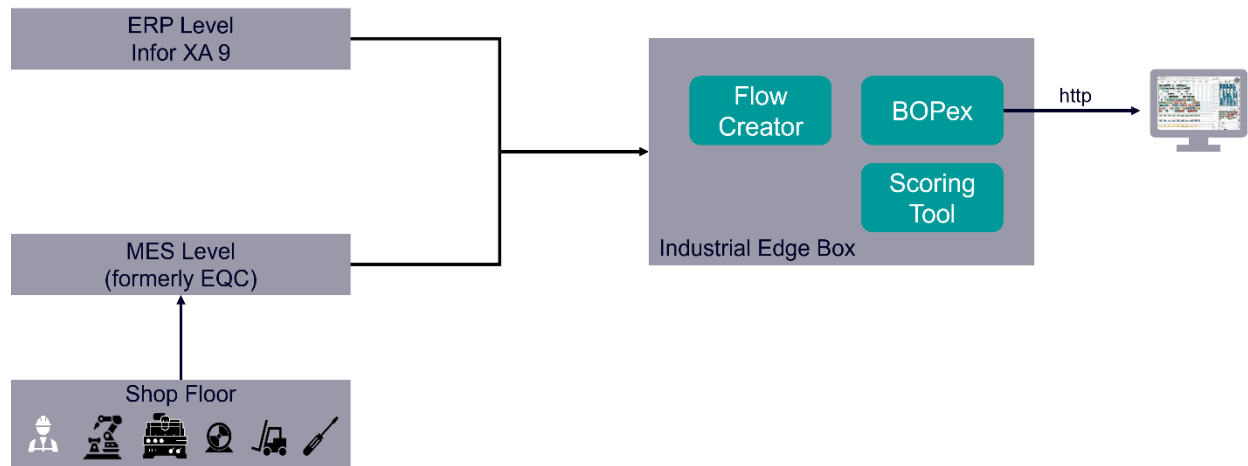


Figure 5 Target Architecture for JLG use-case

Figure 5 shows the proposed architecture for the JLG use-case. The information on the order stack and the Bill-of-materials for these orders as well as current inventory levels is queried from the ERP system, while the information about ongoing orders and their progress is provided from the MES system in place. The data is queried via SQL statements by the tool FlowCreator and converted into the input format for the execution system BOPex. BOPex will provide the engineering capabilities and the interface for operations, which can be accessed as a web-service. The scoring tool is provided as an add-on for BOPex which prioritizes the pending orders based on the availability of their sub-components.

The effectiveness of this prioritization tool was investigated in a detailed use-case study that is explained in the next section.

## JLG Use-case Study

### Simulation Model

The model's architecture is based on the Skytrak assembly line situated at the JLG facility in McConnellsburg, PA. This assembly line encompasses 11 stations, with 10 stations receiving inputs from sub-assemblies. Notably, one assembly station is designated for startup purposes. It is noteworthy that no in-line buffers exist between these assembly stations.

### Inputs and Outputs

The main input to the simulation is a product schedule in the form of a Bill of Materials and the output is the throughput which tells us how many of the input products were finished in what time. This enables us to compare different scheduling strategies and choose the best one.

### Simulation Model Validation, Case Study and KPI Analysis

- Detailed implementation of the simulation model including methods used, input requirements, (with their acceptable formats) and outputs is provided in the attached "JLG Use Case Report".

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- Details on how the model can be further utilized, how parameters can be changed, how schedules can be input and what analysis is done on the results are also provided in the report.
- KPI analysis: Method of KPI analysis is detailed in the report as well.

### *Validation Procedure*

Validation is a crucial step undertaken to verify the accuracy of model parameters, ensuring they faithfully reflect the current state of the manufacturing system. This validation process involves replaying a product schedule used in the production line and meticulously comparing the simulated results with real data. To execute this validation effectively, the following steps can be taken:

1. **Set Initial Parameters:** Assembly station processing times, and buffer capacities between assembly stations and sub-assemblies are set using the import param table. The processing times of sub-assembly workstations are set using the subassembly icons.
2. **Set initial inventory levels and MTBA:** Initial inventory levels are configured to mirror the actual inventory on the real plant floor during the specified consideration period. The levels are adjusted by changing the first column in the inventory tables for tracked parts. It is also crucial to double-check that the Mean Time Between Arrivals (MTBA) for these parts matches the real arrival times in the plant to ensure an accurate simulation. This two-step process ensures that the model closely mimics real-world conditions in terms of initial inventory and part arrival timings.
3. **Find required warmup time to initialize buffers:** Setting initial buffer levels in Tecnomatix involves a trial-and-error approach since there isn't a direct configuration option. To determine the simulation runtime needed for buffers to match the plant floor levels, you iteratively adjust the runtime until the desired buffer state is achieved. This identified time is then inputted into line 2 of the "Time\_Start\_method" as the "Time\_start" variable. This pragmatic method ensures that simulated buffer levels align with the actual conditions on the plant floor, optimizing the accuracy of the manufacturing simulation.
4. **Import Schedule:** The schedule is imported via an excel sheet of the required template to the "BOM\_seq" table.
5. **Run simulation (Product Based):** Simulation is run multiple times and the time required for completion of the schedule is checked through the event controller as shown in Fig 4 top. The average time of completion is checked against the time of completion in the real plant. If within a certain error, the simulation is considered valid. If not, changes to parameters need to be made.
6. **Run simulation (Time Based):** The simulation is run for a fixed period of time and the number of products completed in this period is checked through the drain statistics as shown in Fig 4 bottom. The average number of products completed is checked against the number of products completed in the real plant floor. If within a certain error, the simulation is considered valid. If not, changes to parameters are required.

### **Production Analysis Procedure**

Production Analysis aims to assess the impact of the prioritization tool on JLG plant production. In a Product-Based simulation, the following steps can be undertaken:

#### **1. Ideal Case Simulation:**

- Run the simulation multiple times in an ideal scenario, assuming inventory never depletes. The average time for schedule completion (T1) represents the lower bound for completion time.
- Achieve this by commenting out part of the exit method, and clear guidance on commenting and uncommenting is embedded in the code.

#### **2. Original Schedule Evaluation:**

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- Conduct the simulation multiple times using the original schedule, recording the average time for schedule completion ( $T_0$ ).
- 3. Prioritized Schedule Evaluation:**
  - Run the simulation an equal number of times using the prioritized schedule, recording the average time for schedule completion ( $T_p$ ).
- 4. Calculate Time Savings:**
  - Determine the time saved with the prioritized schedule.
  - Calculate the percentage time savings.
- 5. Performance compared to Ideal Case:**
  - Compute the percentage in time for the prioritized schedule compared to the ideal case.

Alternatively, in a Time-Based simulation:

- 1. Ideal Case Simulation:**
  - Conduct the simulation iteratively under ideal conditions, assuming that inventory never depletes. In this optimal scenario, the production count for a given timeframe represents the upper limit of production for that specific period.
  - Achieve this by commenting out part of the exit method, and clear guidance on commenting and uncommenting is embedded in the code.
- 2. Original Schedule Evaluation:**
  - Run the simulation multiple times using the original schedule, recording the number of parts completed.
- 3. Prioritized Schedule Evaluation:**
  - Run the simulation an equal number of times using the prioritized schedule, recording the number of parts completed.
- 4. Calculate Part Increase:**
  - Determine the increase in the number of parts with the prioritized schedule.
  - Calculate the percentage part increment.
- 6. Performance compared to Ideal Case:**
  - Calculate the percentage of number of produced parts for the prioritized schedule compared to the ideal case.

These steps provide a comprehensive framework for evaluating the effectiveness of the prioritization tool, considering both time and production quantity metrics.

## Conclusion

The simulation model closely aligns with the theoretical maximum output of the system. When considering randomness and comparing it with the real output of the production line, the throughput of the simulation model closely matches the reported production count.

The prioritization tool demonstrates substantial enhancements in throughput improvement, particularly when employed frequently. Even when executed infrequently, it still yields marginal improvements over the unoptimized schedule.

## Landscape Assessment and Guidebook

### Landscape Assessment

The Landscape Assessment is one of the deliverables of this project. This document highlights the gap between academic research and practical manufacturing needs, offering insights into

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the manufacturing industries particularly Small and Medium Manufacturers (SMMs), and their preparedness for implementing real-time dynamic scheduling. This report is divided into three sections as discussed below.

**Academic Literature Review:** This section discusses various scheduling methods such as Artificial Neural Networks, Fuzzy Logic, and Genetic Algorithms. While these methods are extensively studied in theory, their practical implementation, particularly in small and medium-sized factories, is rare. In research papers, it is often unclear whether the methodologies discussed have ever been applied in real production settings, and case studies (when present) do not often include SMMs. It also addresses the general challenges of production scheduling, which include issues like new job orders, machine breakdowns, material routing changes, and dynamic order changes. Traditional static scheduling methods may not manage these dynamic problems effectively, underscoring the need for more adaptive dynamic scheduling approaches. A collection of research journal papers from the past 20 years (2002 – 2022) have been collected and compared with each other to learn the advancement in production scheduling algorithms and tools.

**Industry/Trade Publications:** This section of the report explores how dynamic scheduling is applied across various industries, with particular focus on notable successes. One such example is Laser Precision Inc., which significantly boosted its production by integrating new scheduling systems with enterprise resource planning. While these examples illustrate the benefits of dynamic scheduling, they often fail to provide detailed guidance on how other SMMs can effectively implement these systems. This section aims to show the actual methods and tools that industry practitioners employ to deal with dynamic environments, providing a clearer picture of how dynamic scheduling can be practically applied and the steps necessary for successful implementation.

**Adoption Study:** This section highlights the investigation carried out by Auburn University, where interviews were conducted with various SMMs to gauge their perception of the value of technologies critical to the implementation of dynamic scheduling. These technologies include artificial intelligence, big data, and predictive analytics. The study aimed to understand the current state of adoption of these smart manufacturing technologies and to identify the barriers preventing SMMs from adopting Industry 4.0 practices to the same extent as larger industries. The findings reveal that many SMMs have not yet adopted these technologies and are unprepared for systems that necessitate robust data connectivity and real-time updates. Significant hurdles highlighted include the high initial budgets and complexity associated with these advanced systems, along with a general lack of understanding among SMMs about the benefits these technologies can offer.

## **Guidebook**

The guidebook is also a deliverable from this project. The goal of the guidebook is to help MxD members, in particular SMMs, to understand and use real-time scheduling systems in their production processes. It aims to show manufacturers how to use dynamic production scheduling systems to work more efficiently. Specifically, this report serves as a manual for production managers, industrial engineers, and IT leaders who are considering whether to adopt technological solutions to upgrade their scheduling capabilities.



The guidebook begins with a short introduction and presents the terminology used. The main body then presents a summary of the landscape assessment. Then, it discusses challenges such as the complexity of new technologies, the need for special training, and the initial costs. It provides a clear plan for integrating new systems, including major pitfalls. Moreover, it discusses possible difficulties that SMMs may encounter, like struggle from staff or technical issues with existing software. It suggests solutions and strategies to overcome these hurdles with solutions and phased implementation strategies.

Later, the guidebook talks about how to set up schedules using real-time scheduling software, using Siemens OpCenter APS as an example, since it was used to develop this guide. It covers importing data, choosing scheduling algorithms, and generating schedules. While the guide specifically details using OpCenter APS, the steps are also applicable to other scheduling software with some adjustments. This part is essential for understanding how to effectively use scheduling software to optimize manufacturing operations.

It also talks about the demonstration at ICAMS at Auburn University. And it presents a case study conducted to test how well a real-time scheduling tool improves efficiency at the JLG production plant in McConnellsburg, PA, where they produce a variety of access equipment including boom lifts, telehandlers, and low-level access vehicles across multiple production lines. These examples illustrate how the software uses detailed information about each product and machine to make effective schedules, and how it can be incorporated into operations.

In conclusion, this guidebook is intended as a resource for SMMs looking to improve their production capabilities through advanced scheduling systems. By following the guidebook, manufacturers should be able to improve their scheduling efficiency, adaptability, and response to market changes.

## V. RESULTS

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This section discusses the results of the SMART project with a focus on the scheduling tools that have been developed and demonstrated at Triangle Package Machinery, the ICAMS Lab of Auburn University and the JLG assembly line for the Skytrak telehandler. A list of all deliverables that have been provided to MxD is given in Table 1.

### System Overview

Production scheduling requires making decisions on which order to start next and which workstations to use. If alternative choices are possible, their feasibility has to be evaluated and the best option selected and communicated to the shop floor for execution.

The Receding Horizon Planner is a tool that provides optimized production schedules for a short time horizon in the future. It is intended to be used as an online scheduler, that is running continuously and schedules the next operations for the shop floor shortly before they are due to start. This fully integrated closed-loop operation requires additional software, which provides the connections to the ERP layer and the shop floor. In the context of the SMART project this closed-loop operation has been demonstrated with the Siemens software Opcenter APS both at Triangle Package Machinery and the ICAMS Lab of Auburn University.

At the outset of the project the initial plan was to use the same system setup also for scheduling the assembly line for the JLG use-case. However, the requirements engineering for the JLG use-case showed, that the only degree of freedom in their production planning is the sequence in which the orders are started on the assembly line. Hence, we developed another scheduling tool, which optimizes the order sequence for the final assembly with respect to the availability of critical subcomponents. This reduces the amount of rework that has to be done on items that have already passed the assembly line.

### System Requirements

The scheduler software including Opcenter APS requires a Windows machine – either physical or virtual – with administrator access to install the software.

The data the needs to be provided to the online scheduler includes information about:

- Workstations (name, capacity, etc.)
- Current availability of each workstation
- Operations that are currently executed on a workstation
- Order Stack
- Work plans for each item in the order stack
- Execution status for items in the order stack (if they are partially completed or in progress)

A detailed description of the required data inputs and format is provided in the Developer Documentation for the Receding Horizon Planner Tool as well as the Guidebook (focus on the modelling in Opcenter APS). Both documents are provided as deliverables of the SMART project.



Setting up such a system requires the knowledge of a system integrator. For the operation of the tool a line manager would require a brief introduction how to use the software and should be able use the tool.

### **System Architecture**

The system architecture is shown in Figure 2 for the Triangle & ICAMS use case and Figure 5 for the JLG use case. The description of those architectures is also given in the corresponding sections.

### **Features & Attributes**

Two online scheduling tools were developed and demonstrated in the SMART project:

The Receding Horizon Planner is an online schedule that allows plant managers and shop floor operators to get a suggestion on the next best orders to start at any workstation on their shop floor. This decision is made by an underlying optimization that considers the current status of the shop floor. The scheduling tool is updating continuously in a short (configurable) cycle, so that the schedule automatically considers any deviations from the plan that occurred on the shop floor.

The second tool is a prioritization script, that sorts the pending order stack and prioritizes those operations which (a) have the required materials for completion in sufficient quantity in the inventory and (b) conform to the original master production plan as close as possible.

### **Target Users & Modes of Operation**

The target users for both tools are the plant managers whose job it is to determine the production schedule, i.e. which operations to start next on which workstation.

### **Software Development/Design Documentation**

A detailed description of the required data inputs and format is provided in the Developer Documentation for the Receding Horizon Planner Tool as a deliverable of the SMART project. It is accessible to MxD members according to their membership agreement.



## VI. DISCUSSION & ANALYSIS

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This section discusses the results of the SMART project, including the production increase KPI but also that lessons learned during the execution of the project.

### Industry Impact

Efficient production scheduling in general improves the resource utilization of a shop floor, thus reducing the lead times for orders as well as increasing the output per time. Together this reduces the overall production costs and increases the competitiveness of the manufacturer.

For a static production plan which is not constantly updated, the deviations from the original plan will accumulate over the course of a shift/day and reduce the effectiveness of this plan. With online scheduling, the plan is automatically updated and keeps the production running in the most efficient way.

The SMART project demonstrated the feasibility of online scheduling and provided a compelling case for its benefits with an increase of productivity of more than 12% through order prioritization in the JLG use-case.

Online scheduling is not limited to any industry but can be applied in general to discrete manufacturing use-cases.

### Key Performance Indicators & Metrics

The objective measurement of productivity changes in an ongoing production environment is nearly impossible because a fair comparison requires the same order stand and the same events to happen at the same time. These constant boundary conditions cannot be provided in a real shop floor for a sufficiently large amount of time to get a proper measurement. Therefore, the SMART project used a discrete event simulation to investigate the change in productivity using online scheduling. This investigation was performed for the order prioritization tool in the JLG use-case.

The relevant KPI was the increase in the number of products that could be produced in a fixed amount of time. This was investigated for 1-, 2- and 3-week periods. The improvement of the KPI through prioritization is given in Table 2.

It should be noted that the prioritization tool was only executed once at the beginning of the simulation, thus effectively representing a static plan. This explains why the results are deteriorating for longer simulation runs. Had the scheduler been updated constantly, i.e. at the begging of each day in the simulation, the results for weeks 2 and 3 would have been on the same level as for the 1-week simulation.

*Table 2: KPI's and Metrics*



| METRIC                          | BASELINE | GOAL | RESULTS      | VALIDATION METHOD                           |
|---------------------------------|----------|------|--------------|---------------------------------------------|
| Increased throughput (relative) | 0%       | > 0% | <b>12.7%</b> | Discrete Event Simulation (1 week-scenario) |
| Increased throughput (relative) | 0%       | > 0% | 4.9%         | Discrete Event Simulation (2 week-scenario) |
| Increased throughput (relative) | 0%       | > 0% | 0.3%         | Discrete Event Simulation (3 week-scenario) |

## Accessing the Technology

To access the technology a software that provides shop floor connectivity and the scheduling tool are needed. For a job-shop like production, the suggested toolset would be Siemens Opcenter APS and the Receding Horizon Planner tool. For a flow-shop / assembly line the best tools are Siemens BOPEX and the Prioritization tool. To run the Siemens software a license has to be purchased.

Both for Opcenter APS and BOPEX a system integrator from the Siemens partner-network would be able to integrate the necessary components into the shop floor.

The Receding Horizon Planner and the Prioritization tool are not yet part of a commercial offering at Siemens. However, Siemens is continuing the development of these tools and interested customer would be able to use those tools as pilot customers.

Both the Receding Horizon Planner and the Prioritization tool are provided in executable form as deliverables of the SMART project and can be accessed by MxD members for non-commercial use based on the MxD membership agreement.

## Workforce Development

For the use-cases of Triangle as well as the ICAMS Lab, the online scheduler has been deployed to the shop floor. As a consequence, the machine operators (in the ICAMS lab) and the dispatcher (for Triangle) had to use the online scheduling software and have been able to do that after a brief introduction.

Furthermore, the demonstration at the ICAMS lab enables manufacturers to test online scheduling and train the operators on this system if needed.

The learnings from these projects are also planned to become part of the training for interested students in the field of industrial engineering at University of Virginia and Auburn University.

## Lessons Learned

A major deviation from the initial plan of the project happened at the JLG use-case. Because a connection to their legacy database system could not be established within the execution period of this project, we fell back to running the scheduler manually with input and output data being exchanged via text-files.

The database connection could have probably been established as planned, if (a) we have had the knowledge of an expert for the legacy system that was in place or (b) we have had the services of a professional system integrator.



Even though we could not run the prioritization tool with online data from the shop floor, we could still investigate the effectiveness of the prioritization tool with the back-to-back comparison by means of the simulation of the shop floor.

A deviation from the original project plan was the extent to which the online scheduler would be used in productive operations. In the Triangle use-case the online scheduler was developed, integrated and ready to use by the dispatcher. The dispatcher even met with the project team and confirmed the feasibility of the schedule. However, when not explicitly invited by the project team to do so, the dispatcher did not use the online scheduling software on his own.

The reason for this lack of use is because the dispatcher is currently distributing the information about the scheduler manually by handing out color-coded order-routings to the machine operators. This is happening once or twice a day. If online scheduling provides updated schedules every few minutes, it dramatically increases the workload of the dispatcher to just distribute the latest schedule – and reduces his time to work on other tasks. An important requirement for online scheduling is therefore an automatic distribution of schedule updates to the workstation operators.

Even though the dispatcher did not actively use the schedule, we could successfully generate these schedules based on the live data from the shop floor and showed that we created feasible schedules in very short intervals.

Therefore, the recommendations for future practitioners of online scheduling are:

- 1) Plan generously for system integration, especially for older systems. Use a professional system integrator.
- 2) Make sure, that you have a way of automatically distributing the production schedule to the workstation operators, e.g. consider installing screens next to your workstations.

## VII. CONCLUSIONS & FUTURE WORK

### Next Steps & Challenges

The results of this project have been presented to MxD and its interested members and the project team is happy to engage with any interested member directly.

Regarding the academic distribution of these results, the SMART project team included two PhD students who will continue to distribute their contributions and learnings from the SMART project to the academic community via publications and their theses.

Regarding the commercialization strategy, the SMART project has implemented and demonstrated online scheduling based on a prototype that has been developed by the Siemens Technology branch. To guarantee ongoing product support and maintenance, this prototype must be adopted by a Siemens Business Unit and transferred into product development. With its interface to the Siemens software Opcenter APS, the developed solution supports this transfer into a product development stage.

Siemens is currently continuing with the integration efforts for the online scheduling tool and would be able to provide a solution for interested pilot customers. Given this customer interest in the application, online scheduling should become a commercial offering within the next few years.

### Transition Plan

#### Transition Chart

*The transition chart provides a catalog of all of the project deliverables and their respective transition route. Deliverables can transition through deployment at an industry member's site, as an educational reference or through a commercialization effort. Each of these transition routes are detailed in this plan.*

| Transition Chart |                                             |                                                                                                                            |                       |                        |           |               |
|------------------|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|-----------------------|------------------------|-----------|---------------|
| #                | Deliverable Name                            | Description                                                                                                                | Format of Delivery    | Technology Integration | Education | Commercialize |
| 1                | Landscape Assessment                        | Conduct an asset audit of enterprise systems, data collection mechanisms (e.g. sensors), and define baseline KPIs, metrics | Written Report (.pdf) |                        | X         |               |
| 2                | Data Architecture and Integration Framework | Documentation of the data architecture and integration framework including approach, diagrams, and considerations          | Written Report (.pdf) | X                      |           |               |



|    |                                      |                                                                                                                                  |                              |   |   |   |
|----|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|------------------------------|---|---|---|
|    |                                      | for compliance and security                                                                                                      |                              |   |   |   |
| 3  | Implementation at Large Manufacturer | Implementation of the Siemens scheduling solution at Oshkosh's access vehicles assembly site and validation of its effectiveness | Docker-Container             | X |   | X |
| 4  | Implementation at SMM Manufacturer   | Implementation of the Siemens scheduling solution at Triangles's manufacturing site and validation of its effectiveness          | Docker-Container             | X |   | X |
| 5  | Discrete Event Simulation Model      | A simulation model of the one of the manufacturing sites for detailed analysis of ROI                                            | Plant Simulation File (.spp) | X | X |   |
| 6  | Guidebook                            | A general guidebook detailing best practices for choosing a scheduling solution and common pitfalls to avoid                     | Written Report (.pdf)        | X | X |   |
| 7  | Detailed Case Study                  | A case study providing a detailed account of the implementation with a focus on ROI and lessons learned                          | Written Report (.pdf)        |   | X |   |
| 8  | Technical Demonstrations at MxD      | Demonstration of technical research and development outcomes in MxD's factory                                                    | Presentation (.pptx)         |   | X |   |
| 9  | Software: Online Scheduler           | Executable version of the scheduling software                                                                                    | Executable Program (.exe)    | X |   | X |
| 10 | Developer Documentation              | Includes software documentation, integration documentation, documentation for modifications to software, documentation of        | Written Report (.pdf)        | X | X |   |

Distribution Statement A. Approved for public release: Distribution Unlimited.



|                            |                                    |                                                                                                 |                             |  |   |  |
|----------------------------|------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------|--|---|--|
|                            |                                    | known bugs and issues                                                                           |                             |  |   |  |
| 11                         | Technology Transition Workshop     | Workshop for MxD members on scheduling technology and possible applications at ICAMS facilities | Online / In-person workshop |  | X |  |
| <b>Additional Outcomes</b> |                                    |                                                                                                 |                             |  |   |  |
|                            | Educational Component (UAV Course) | Generalized model, embedded into graduate coursework                                            |                             |  | X |  |

### Transition Summary

*The transition summary contains a concise statement explaining the transition activities for each deliverable. In other words, how do you expect the deliverable will be used/consumed/deployed after the project period of performance. Deliverables that will be transitioned through multiple routes must have a transition statement for each of those activities.*

*For each deliverable, give a one sentence summary of the transition activities that describes how the deliverable will be deployed or consumed.*

#### *Deliverable 1 – Landscape Assessment*

- **Education:** Auburn University has created a Landscape Assessment. This document will be used to educate manufacturers interested in real-time scheduling so that they can evaluate their readiness to implement real-time scheduling solutions and whether it is the right decision for their organization.

#### *Deliverable 2 – Data Architecture and Integration Framework*

- **Technology Integration:** Prior to the implementation, Siemens, JLG and Triangle will document the data and integration setup for their respective use-cases. This provides a solution template for future users of real-time scheduling and at the same time documents the required input data and connectivity requirements.

#### *Deliverable 3 – Implementation at Large Manufacturer*

- **Technology Integration:** JLG will deploy an order sequencing software for the JLG SkyTrak assembly line at McConnellsburg, PA. The software will work without direct connection to the shop floor IT but get the required input from data exports of the ERP system. This allows for an evaluation of the sequencing software through JLG, before a decision for a permanent and integrated deployment can be made.
- **Commercialization:** Order Sequencing happens before the detailed online scheduling will start to account for the material availability. The Order Sequencing software will not directly be commercially available but can be added to the online scheduler in a later stage.



#### *Deliverable 4 – Implementation at SMM Manufacturer*

- **Technology Integration:** Triangle has deployed the real-time optimization software at their manufacturing site in Chicago to assess the benefits of this method and gain trust from the production planners on site before a decision about a permanent deployment is made.
- Triangle has established a direct link between the ERP database and the Siemens scheduling software Opcenter APS. Triangle has crafted the essential queries for seamless data transfer and the creation of required data tables in the scheduling software. This process facilitates APS in generating preliminary schedules for user review. It involves an iterative approach to refining input/output specifications, ensuring the development of a usable and optimal schedule. Introducing the tool to end users early on is highly advantageous for fostering trust and gaining their support.
- Triangle ensures the proper data availability such as: correct BOMs, routings with setup and run times as well as defined work centers.
- Triangle and Siemens have modelled the scheduling problem in Opcenter APS to reflect the real-world constraints on the shop floor. This includes identifying Infinite capacity work centers for outside processing, warehousing and occasionally QC.
- Siemens has provided and integrated a real-time optimization algorithm, that observes all constraints and runs in an unattended loop with a configurable update cycle time.
- **Commercialization:** The real-time optimization has been prototypically integrated into the commercial scheduling software Opcenter APS.

#### *Deliverable 5 – Discrete Event Simulation Model*

- **Technology Integration:** Simulation Model for JLG SkyTrak assembly line has been built on the Siemens Tecnomatix modeling software. The simulation model (.spp) file is attached as deliverable.
- **Education:** The simulation model can be potentially used to educate JLG engineers so that they can modify the parameters and inputs to learn “what if” analysis to improve the future plan of their operation

#### *Deliverable 6 – Guidebook*

- **Technology Integration:** JLG and Triangle can use the Guidebook as best practice examples for their scheduling efforts.
- **Education:** Guidebook will be used to educate manufacturers interested in real-time scheduling so that they can implement the real-time scheduler at their organization

#### *Deliverable 7 – Detailed Case Study*



- **Education:** The detailed case study from the JLG SkyTrak assembly line can potentially be used to educate future manufacturing engineers so that they can learn about the practical challenges for efficiently feeding an assembly line.

#### *Deliverable 8 – Technical Demonstrations at MxD*

- **Education:** The technical demonstrations at MxD will be used to educate other MxD members so that they can learn the prerequisites and benefits of real-time scheduling and assess how useful that method is for their own production site.

#### *Deliverable 9 – Software: Online Scheduler*

- **Technology Integration:** Siemens has deployed the online scheduling software at the Triangle manufacturing site in Chicago to demonstrate the integration of online scheduling in a commercial setup.
- **Commercialization:** The Online Scheduler software will become a commercialized offering of Siemens integrated into their Opcenter APS portfolio to address the needs of customers with a flexible production setup.

#### *Deliverable 10 – Developer Documentation*

- **Technology Integration:** Siemens will provide a Developer Documentation for their Online Scheduler software so that other MxD member are able to test the system for themselves before deciding for a commercial integration.
- **Education:** The developer documentation will be used to educate other MxD member on the requirements and functionality of online scheduling.

#### *Deliverable 11 – Technology Transition Workshop*

- **Education:** The Technology Transition Workshop at the ICAMS Lab of Auburn University demonstrates the online scheduler on a real shop floor but still accessible for interested MxD members. This workshop will be used to demonstrate the Online Scheduler to other MxD members who are interested in online scheduling for their own manufacturing sites.

## **VIII. APPENDICES**

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### **Appendix A: Abbreviations and Acronyms**



RHP – Receding Horizon Planner

ERP – Enterprise Resource Planning

APS – Advanced Planning and Scheduling

ICAMS – Interdisciplinary Center for Advanced Manufacturing Systems

SMART – MxD 21-06-01 Scheduling for Manufacturing Operations in Real-Time

Skytrak – model name of the telehandler that is assembled in the JLG use-case

Opcenter APS – name of the Siemens commercial scheduling software

BOPex – name of the Siemens commercial manufacturing execution software



## Appendix B: Demos

The software for the demonstrations both a Triangle and JLG have been provided as deliverables to MxD in the form of a docker container (Triangle use-case) and executable file (JLG use-case) including instructions of how to use these files. They are available to MxD members in accordance with the membership agreement.



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## Appendix C: Validation & Testing

N/A



## **Appendix D: User Resources**

A developer documentation for the online scheduler software and system architecture as well as the Guidebook, Landscape Assessment and Detailed description of the JLG use-case have been provided as deliverables of the SMART project to MxD and are available to MxD members in accordance with the IP Management Plan of this project.

The list of all deliverables that have been provided to MxD can be found in Table 1.