Using Discrete Event Simulation in multiple System Life Cycles to support Zero-Defect Composite Manufacturing in Aerospace Industry

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Abstract: Time-consuming manual in-situ visual inspections are a big challenge, in the manufacturing process of carbon fibre wing covers in aerospace industry. In the EU research project ZAero (Zero-defect manufacturing of composite parts in the aerospace industry) in-situ manual inspection on fibre placement stations thus shall be replaced by automatic inline inspection. To quantify the improvements of the suggested process changes, experiment series performed by a discrete event simulation (DES) model were needed to provide necessary key performance indicators (KPI). As the new inline inspection detects events and provides a lot of additional data for them, the simulation model proved to be very useful to support a decision support system (DSS) to help decision makers in determining which of the events count as defects and need to be reworked. In our work we show that a DES model, when proper implemented, is as versatile as a Swiss knife and can make valuable contributions to more than one life cycle of a manufacturing system.

Keywords: Discrete-event Modeling and Simulation, Zero-Defect Manufacturing, Decision Support Systems, Automated Fiber Placement, CFRP Production, Aerospace Engineering, Digital Twin

1. INTRODUCTION

The aim of the EU project 'Zero-defect manufacturing of composite parts in the aerospace industry' (ZAero) (Eitzinger, 2016) is the development of inline quality control methods for carbon fibre reinforced polymer (CFRP) parts production and decision support systems to achieve:

- Reduction of production costs through reduction of manual in-situ inspection processes during lay-up, of post-process testing after curing and of end-of-line rework.
- Increased production flexibility and higher production rates through inline quality control by avoiding productivity losses caused by in-situ manual inspection work.
- Reduction of waste and scrap through earlier re-work processes, inline monitoring and process control.

Technologies used for automated lay-up include automated (dry) fibre placement (AFP) and automated dry material placement (ADMP®) (Rodriguez et al., 2018). This paper focuses on the AFP process.

AFP is an important manufacturing process for aerospace components, say (Schmidt et al., 2017), and they claim that at the time their research was created, there was no monitoring system in place that could reliably detect all crucial defects (gaps, overlaps, splice, fuzzball . . .).

In ZAero, combining data from a fibre orientation sensor (FScan), which uses a carbon fibre reflection model to measure fibre orientation (Zambal et al., 2015), and data from a laser profile scanner (LScan), which captures 3D profiles, is used to detect these defects. Furthermore Electrical Time Domain Reflectometry (E-TDR) (Gleuher et al., 2018) is used to monitor flow fronts and the degree of cure during the infusion and curing process.

Part flow simulation (PFS) and in special discrete event simulation (DES) has proven its usefulness in innumerable application cases in manufacturing (Avventuroso et al., 2018; Kampa et al., 2017). According to (Polenghi et al., 2018) a trend of increase in the number of application fields of simulation in industrial engineering exists. They also detect a trend of shifting from design simulation to more life cycle simulation for operations management.

In the ZAero project simulation tools are developed to optimize the flow of parts through production, taking inline process control into account. This is necessary, because the proposed changes in inline quality inspection and rework on fibre placement, as well as the flow front and curing monitoring will also affect the process durations and thereby the part flow in a multi-stage manufacturing system. The DES model is then used to investigate and compare key performance indicators (KPIs) from current manual in-situ inspection technology with KPIs for the proposed new inline quality control and monitoring process.

Manuscript 253 submitted to 9th IFAC Conference on Manufacturing Modelling, Management and Control. Received December 14, 2018.

One additional key aspect in the ZAero project is: How to deal with the new data about features, that can be detected by the inline-inspection system? Within the project, a decision support system (DSS) prototype was developed, to assist the operator decide, which of the recognized features should be reworked. The simulation model can make an additional contribution to the planning of the DSS. And finally the DES model can also be used to generate simulated manufacturing execution system (MES) / production data acquisition (PDA) data. This data helps to research how the feature data can be used in real production at an early development stage, as long as real data is not available (e.g. when more features than usual are detected at an AFP inspection station, preventive maintenance (PM) of this station may be required).

Unlike (Wang, 2013), ZAero does not use data mining to move towards zero-defect manufacturing (ZDM), but implemented a new approach for inline lay-up inspection. For the AFP process (Rudberg et al., 2014) point out that downtimes of AFP machines for manual inspection and rework in their large scale AFP lay-up cells can take up to 32% of machines production time; Therefore, replacing manual in-situ inspections with inline lay-up inspection can quickly pay off. However, it is questionable how a reduction in rework time will affect the KPIs of the plant.

The rest of the paper is structured as follows; Section 2 provides an overview of the composite parts manufacturing process and explains the requirements for the simulation model to support both, design simulation and simulation for operations management. In Section 3 the impact of ZDM on wing cover production line is quantified by comparing KPIs, DES supporting a DSS, and using DES as a MES data generator is shown. Finally, Section 4 comprises our conclusions of the paper.

2. APPROACH

2.1 CFRP production process

The demo parts realized in the ZAero research project are only a part of a real wing cover with increasing complexity (Rodriguez et al., 2018). On the contrary, part flow simulation deals with the manufacturing process of a full size wing cover. The process of the ZAero project shown in Figure 1 is based on real processes in manufacturing of a CFRP part in aerospace industry (e.g. wing cover of A350XWB) and is structured into 3 main areas:

Clean Area:

- P0: Mould Preparation (MP): Prepare mould for downstream material placement.
- P1: Fibre Layup (AFP): Place material on the mould in multiple layers; in situ-inspection and optional rework.
- P2: Stringer Mounting (SM): Stringers are mounted. The stringers are produced near the assembly station and are stored near the station. The model assumes that at any given time enough stringers are available.
- P3: Infusion Bag (IB): The part is prepared for the subsequent furnace process and then hermetically sealed.

Oven Zone:

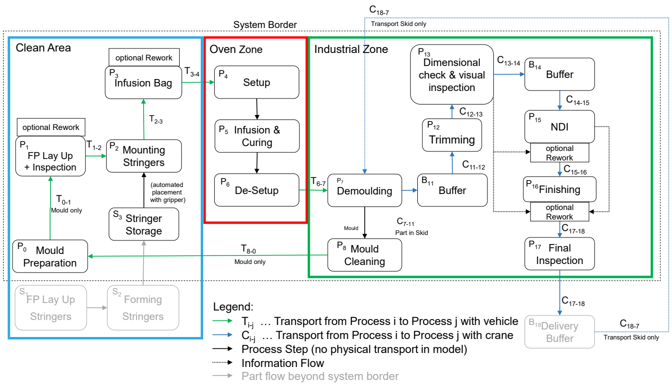


Fig. 1. ZAero Process Schema: Clean Area, Oven Zone, Industrial Zone

- P4: Infusion & Curing Setup: Installation of all needed devices, sensors, connectors . . .
- P5: Infusion & Curing (IC): Infusion of resin, curing.
- P6: Infusion & Curing De-Setup: Dismounting of all devices . . .

Industrial Zone:

- P7: Demoulding (DMC): Remove part from mould. Attach clamps for crane gripper.
- P8: Mould Cleaning (DMC): Clean and basic preparation of mould before next use.
- P12: Trimming (TRI): Machining for proper dimensions.
- P13: Dimensional Check & Visual Inspection (DIM): Required rework is postponed to upcoming rework stations.
- P15: Non Destructive Inspection (NDI): Optional rework when defects are found.
- P16: Finishing & Rework (FR): Optional rework of slight imperfections.
- P17: Final Inspection (FI): Final step before delivery.

For the industrial zone, conventional scenario and ZDM scenario do not differ. The main difference of both scenarios is, that in ZDM an automatic inline inspection system (P1) is used to detect and classify features, whereas in the conventional scenario features are detected by manual in-situ inspections. If defect-rework is necessary, both scenarios use manual or semi-automatic rework procedures. The process experts assume, that in ZDM less rework will occur, because a structural simulation, that calculates margin of safety (MoS) for features, is connected with the optical defect detection and this enables the system to dispense with rework of features, that are neither critical in MoS nor due to their classification and/or size. Furthermore, in the ZDM scenario a shortened curing time is assumed due to the better knowledge of the degree of completion by monitoring the flow front and the curing degree.

Because of the planned productivity of about 60 parts per month, it is necessary that some processes have to be performed on $1 \ldots n$ stations, which work in parallel.

Some of the processes need an additional inspection and an optional rework workstep, depending on the result of the inspection. The rework may be performed in place at the station (P1, P3, P16) or on a dedicated rework station (P15).

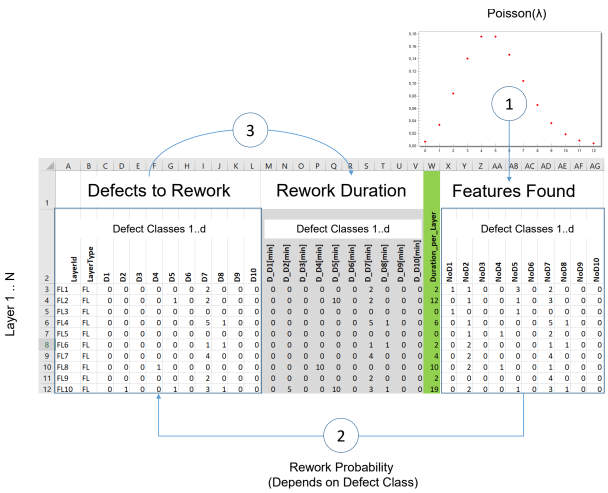


Fig. 2. From Features to Rework-Duration

All composite parts always require a mould for creation and also for handling until the curing process is finished. Automated guided vehicles (AGV) transport moulds, with or without part, from one process to the successor. AGVs may enter or leave the clean area only via a lock. AGVs are equipped with mecanum wheels (Dickerson and Lapin, 1991), which let them move not only forward and backward, but also sideways.

In the industrial zone a portal crane moves the part (which is inserted into a workholding device) from one process station to the next station. Whenever no station for the upcoming process is available, the part is moved into a buffer storage. Though there are preferred positions within the buffer, depending on the position of the station on the shop floor in order to minimize PC movements, all places of the buffer can store all parts at each production stage. This allows a very flexible layout and ensures sufficient amount of buffer space.

2.2 Defects modeling

The process duration on AFP stations depends on the number and classification of features. The model uses a three-stage procedure for the calculation of rework duration for each layer (Figure 2).

(1) calculate the integer number of found features by means of a stochastic poisson function
(2) decide for each feature, whether it is a defect that needs to be reworked with a given probability (uniform distribution)
(3) calculate the actual rework duration for this layer

The average number of features for a given defect class is the input for the poisson distribution and depends on the actual layer type. Our complex CFRP part consists of three different layer types with a total of 180 layers. The average number of features per layer type, the rework probability and the rework duration can be defined for every defect class. The total duration of the rework is calculated from the sum of all defects, that need to be reworked. All parameters can be modified manually or can be read in from predefined settings tables, e.g. for ZDM and conventional scenarios. In the specific case of rework, the station then requests a worker (team) with the appropriate skills to carry out the rework.

2.3 Using DES in multiple system life cycle phases

The use of DES can support the ZAero project in several ways. Specifically, the project planned to use DES in the life cycles Beginning of Life (BOL)

- Study / logistical simulation
  (Compare KPIs of 'In-situ', ADMP, AFP)
  = BOL - System design
- MES = generate simulated order tracing data
  (To see the usefulness of the defect data for operations planning and PM)
  = BOL - Process design

and Middle-Of-Life (MOL)

- Execute experiment series for future scenarios to provide assistance for the DSS
  = MOL - Operations Planning

of the ZAero system. For our MOL / DSS usage of the DES, the simulation model must be capable to

- read current job data from a ERP / MES
- initialize the plant model using this data
- write data during / at the end of simulations runs

(Bergmann and Straßburger, 2015) describe in their work the experiences they made when using the Core Manufacturing Simulation Data (CMSD) XML standard for the purpose of simulation model initialization and simulation output data collection. Initialization of simulation models is part of the more general Automatic Model Generation (AMG) concept, for which more research is described in (Krenczyk et al., 2016). (Lüder and Schmidt, 2017) evaluated the applicability of AutomationML, an upcoming open object-oriented XML-based storage and exchange format in industry 4.0 context, which calls for increased integration in various directions with regard to the structure and design/creation/use of production systems.

In our case we do not need automatic model generation, because the model configuration (e.g. the number of active AFP stations) can be changed by parameters and there is no need to build new models. We initially use simulation tool data structures for model initialization of the current system state and the MS-SQL database tables shown in Figure 3 for writing data.

3. RESULTS

3.1 Verifying ZDM productivity increase using DES

First a simulation model for the design and optimization of a CFRP part production site was created, by using the discrete event simulation tool "Tecnomatix Plant Simulation" from Siemens. By the help of this model the impact of ZDM versus conventional production was evaluated. Requirements for the simulation study were: scalable layout, deadlock proof transport system, widely configurable (one model for all scenarios) and nice visualisation for presentation and validation. In Figure 4 the simple but easily expandable layout for the ZAero project is shown.

Manuscript 253 submitted to 9th IFAC Conference on Manufacturing Modelling, Management and Control. Received December 14, 2018.

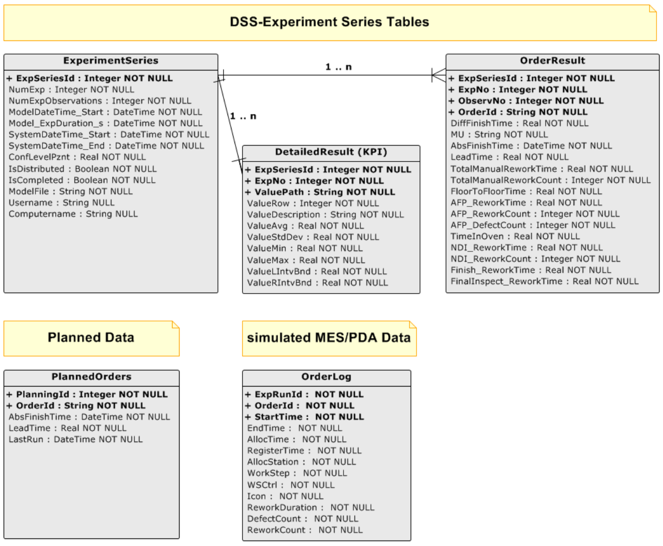


Fig. 3. ER Diagram of Simulation/MES-Database

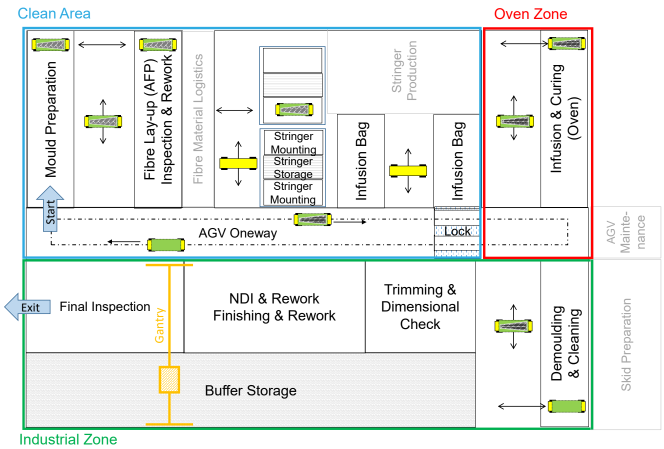


Fig. 4. Plant Layout Schema Wing Cover Manufacturing

The model layout basically follows an U-shape. Within the clean area and the oven zone parallel stations are placed along aisles, which allows for every work step the placement of a flexible number of stations. Because of an unidirectional AGV track, which connects the aisles, AGV deadlocks are avoided. Within an aisle the AGV must move in all directions, but each aisle is serviced by only one dedicated AGV. The number of active fibre lay-up stations can be parametrized, up to a maximum of 12 stations

The required settings for ZDM and conventional manufacturing processes can be easily adapted, as well as for AFP and ADMP process. The major requirement for the design of the DES for the future A320 neo production, is the planned production rate of 60 parts per month. From this target value, a plant layout was created that contains 12 lay-up stations. In a basic experiment, different numbers of active lay-up stations were investigated. Figures 5 and 6 show the KPIs 'Parts per Month' and 'Average Leadtime' for different numbers of AFP stations and a comparison of ZDM versus Conventional Manufacturing. Clearly, the goal of 60 parts per months is not achieved with 8 lay-up stations. A throughput of more than 60 parts per month is achieved with 10 lay-up stations for both, the conventional

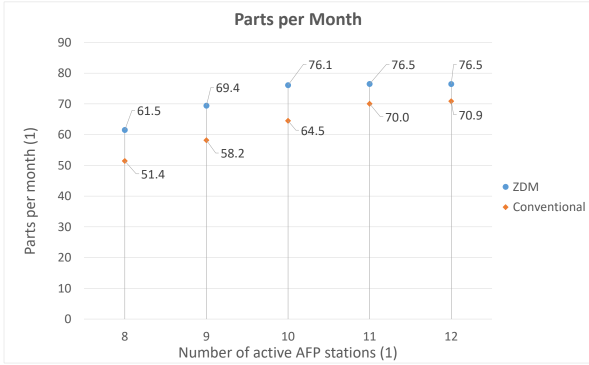


Fig. 5. KPI 'Parts per Month': ZDM vs. Conventional Manufacturing on Number of AFP Stations

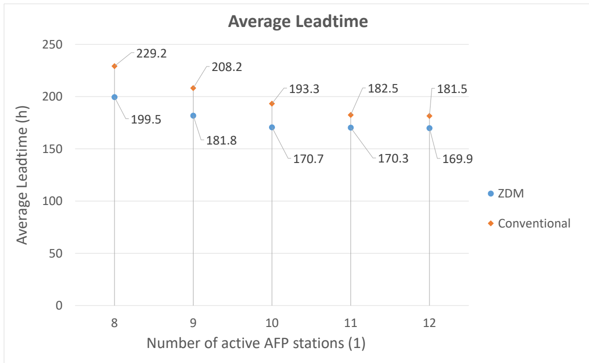


Fig. 6. KPI 'Average Leadtime': ZDM vs. Conventional Manufacturing on Number of AFP Stations

and the ZDM scenario. With the use of 12 lay-up stations the targeted throughput rate is clearly reached for both, but the difference of non-ZDM and ZDM will become less significant. The time distribution of the ZAero AFP machines is shown in Figure 7. In our setting, 13.3% of the AFP machine time can be saved by omitting the in-situ inspection time with ZDM. Though the duration of inspection and re-work of a single defect of an CFRP part is rather small compared to the overall time, needed for the production of a complete part, the time effort for inspection and rework is considerable in total. As the number of defects increase with the volume of a part, this is especially true for medium to large parts, which are often needed in aerospace industry.

However, as depicted in Figure 5 for the desired production rate with ZDM two AFP machines could be saved. On average in all scenarios ZDM boosts the KPI 'Parts per Month' by 14.8%!

3.2 Using the DES as an MES-data generator

One question in the ZAero project is: How to deal with the new data about features, that can be detected by the inline-inspection system? Thus, we used the DES model as a data-generator to generate simulated MES/PDA data, to research how the feature data can be used in real

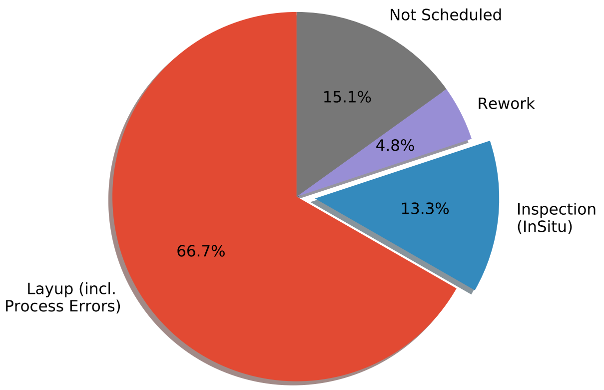


Fig. 7. AFP Machines - Time Distribution

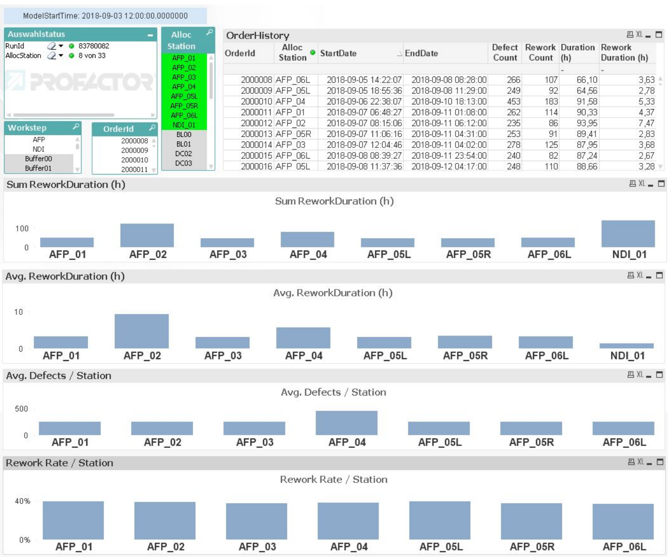


Fig. 8. Evaluation of MES-data in Analytic tool

production later. We used the simple table layout for 'OrderLog' shown in Figure 3 to save MES data. If e.g. some inspection station detects more features than usual, it may be concluded that PM of this inspection station is required. In Figure 8 some experiment results can be seen, where misbehaving AFP-stations were simulated. Operators may conclude that they need to plan maintenance for AFP_04.

3.3 DES support for the ZAero DSS tool

Simulation can also help in supporting DSS systems (Heilala et al., 2010). Having a digital-twin of the manufacturing system, it seems obvious to make use of the part flow simulation for medium term management decisions like changes in personnel capacity or shift management. One goal of the project is also to investigate how quality management in production can be supported with production-relevant forecast data. To deliver a good forecast, the simulation model also depends on realistic process parameters, which should be calculated and regularly updated on the basis of actual error rates and rework times, as soon as enough data is available. Nevertheless there will be some uncertainty, in particular because of the unknown results of upcoming AFP inspection results and

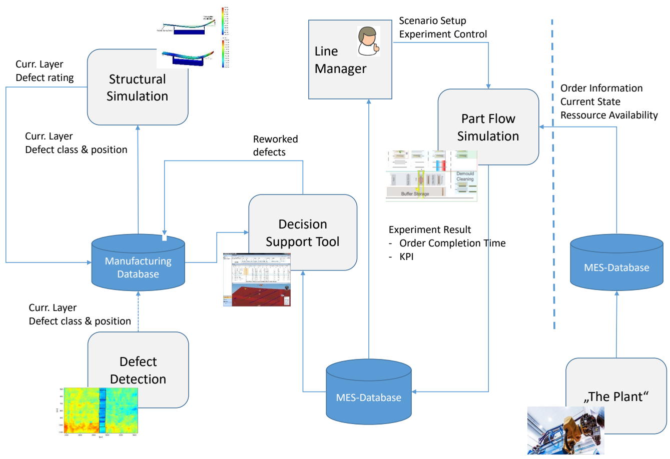


Fig. 9. DSS System collaboration

additional rework. Therefore the simulation experiments are performed with different defect probabilities and the results of all experiment series are made available to the DSS via a SQL database.

The requirements for supporting DSS are model initialisation from given states, fast experiment execution and communication with DSS (MS-SQL database). For DSS-support experiment series are run periodically (every 15 minutes) that first initialize the simulation model with current plant settings, and then e.g. simulate system behaviour if operators choose to rework more than the necessary rework defects. Within the project, the execution of a specially configured simulation model provides a realistic initial state of the production line at a certain point in time. In real production, a MES can deliver the current state of the plant. This includes work in progress and upcoming orders, position and state of transporters and current station state as well as process progress. The initialization has to take care, that also objects that are responsible for controlling the sequence are initialized according to the current queue sequence.

The results for DSS are calculated based on many model executions (e.g. 96 replications per experiment run) and with different random generator settings. Simulation results are written then into an MS-SQL database (see Figures 9, 3). The Decision Support Tool then reads this database and assists operators on AFP stations with their decisions, how much of the defects found and classified by inline quality control system shall be reworked without causing too much disturbances in production (i.e. deliver the desired amount of products in time). To rework more may lead to less rework to be done in later stages, but should only be done if order delivery is not critical.

Figure 10 shows e.g. the distribution of order delay in hours for order '2000098' and each rework strategy. And in Figure 11 the corresponding DSS output to support operators decision to rework more is depicted. For the DSS we visualize whether the rather pessimistic 95th percentile of the order *FinishTime* is in time.

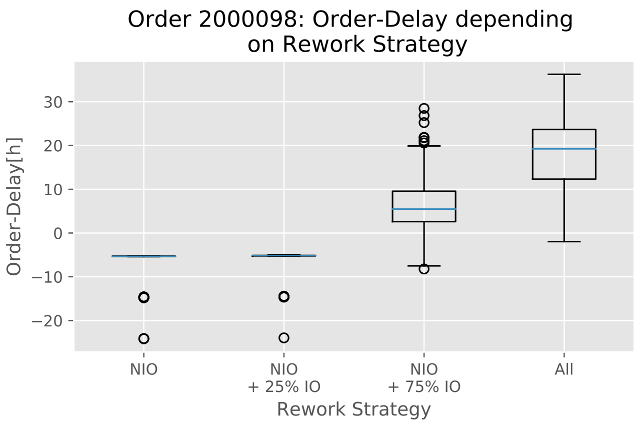
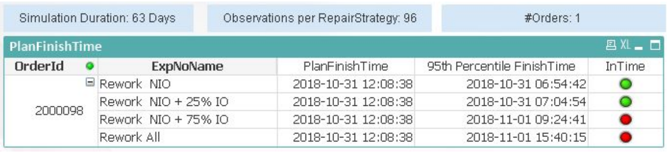


Fig. 10. BoxPlot Order-Delay[h] for Order 2000098 depending on Rework Strategy



Simulation Duration: 63 Days | Observations per RepairStrategy: 96 | #Orders: 1

PlanFinishTime

OrderId	ExpNoName	PlanFinishTime	95th Percentile FinishTime	InTime
2000098	Rework NIO	2018-10-31 12:08:38	2018-10-31 06:54:42	green
	Rework NIO + 25% IO	2018-10-31 12:08:38	2018-10-31 07:04:54	green
	Rework NIO + 75% IO	2018-10-31 12:08:38	2018-11-01 09:24:41	red
	Rework All	2018-10-31 12:08:38	2018-11-01 15:40:15	red

Fig. 11. DSS Output for Order 2000098 depending on Rework Strategy

4. CONCLUSIONS AND FUTURE WORK

When we move toward zero defect manufacturing with improved processes like automatic inline quality inspection or monitoring of curing process, overall process duration of lay-up stations as well as time in oven will be reduced. To maximize the benefits of the adopted single process steps, it is advantageous to look at the whole production system. We developed a DES model to support the development of a manufacturing site for aircraft wing cover and investigated the influence of the process improvement. Our experiment series showed, that the proposed ZDM system in our setting has an advantage of about 14.8% in productivity.

In ZAero project DES was not only used for manufacturing process engineering and optimization, but also to support analysis and optimization during production phase. The simulation model has proved to be very useful for the development of a DSS and it could easily be used as a mock up for a real plant and the controlling MES to provide life-like test data. DES has shown that it can provide valuable support in multiple stages of the life cycle of our ZAero ZDM production system.

In further project steps the simulation model will be evolved to better support NDI rework decrease if more AFP-rework was done, and planning parametrization and execution of experiment series will be enhanced.

ACKNOWLEDGEMENTS

This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 721362 (project ZAero) and by the government of Upper Austria (project DigiManu).

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