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SIMULATION OF LOW-VOLUME MIXED MODEL ASSEMBLY LINES: MODELING ASPECTS AND CASE STUDY

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ABSTRACT

In this paper, we consider the modeling and simulation of low-volume mixed model assembly lines that can be found in the aerospace industry. Low-volume mixed model assembly processes are characterized by a large amount of tasks to be manually performed, buffer space constraints, specialized resources like jigs and tools, and a large number of external suppliers. The main principles of modeling and simulating such manufacturing systems are discussed. Based on a domain analysis, the major building blocks of simulation models for low-volume mixed model assembly lines are derived. We exemplify their implementation using the commercial discrete-event simulation tool AutoSched AP. As an application of these building blocks, we analyze the cabin installation process in a final assembly line in aircraft production using discrete-event simulation.

1 INTRODUCTION

The aerospace industry is characterized by a labor-intensive, low-volume production. Mixed model assembly lines are typical where different product models, i.e. airplanes, with different processing times are manufactured on the same assembly line. Complex assembly operations have to be performed on aircraft structures (cf. Heike et al. 2001, Mas et al. 2013 amongst others). A large number of suppliers are involved in the production of airplanes. The parts and services provided by the different suppliers are responsible for up to 80% of the final costs of products in the aerospace industry (cf. Tang, Goetschalckx, and McGinnis 2013). The involved suppliers are a source of variability in the manufacturing systems of the aerospace industry. Discrete-event simulation has the potential to play an important role in aerospace companies (cf. Murphy and Perera 2002). However, it seems that simulation is used more often in the early design phase of an airplane than for the support of production planning and control-related decisions (cf. Jahangirian et al. 2010 for a recent survey on simulation applications in manufacturing). This situation is caused by the fact that there are differences between high-volume and low-volume manufacturing that lead to unique features of simulation approaches in the aerospace industry and hinder to a certain extent a broad application of simulation techniques in this domain.

In the present paper, we are interested in identifying and exploring the differences between the two domains. We show that the low-volume production in the aerospace industry is similar to one-of-a-kind production processes in shipbuilding or in construction of buildings (cf. Spieckermann 2011, Steinhauer and Soyka 2012), while there are also some significant differences at the same time. We are interested in deriving building blocks for simulation models of low-volume mixed model assembly lines based on the derived domain characteristics.

The paper is organized as follows. We describe important domain characteristics of low-volume assembly lines in Section 2. In addition, related literature is discussed in this section. Major ingredients of a simulation model for the domain of low-volume mixed model assembly lines and their implementation using the simulation engine AutoSched AP are discussed in Section 3. These building blocks are used to model and simulate the cabin installation process of a final assembly line in the aerospace industry in Section 4. Some simulation results are presented. Finally, we conclude and discuss future research directions.

2 MODELING AND SIMULATION OF LOW VOLUME MIX MODEL ASSEMBLY LINES

2.1 Domain Characteristics

We start by describing the base system. It consists of several flow lines (cf. Mas et al. 2013) in large-size production facilities (cf. Scott 1994). Each flow line is formed by a set of stations that are arranged in a consecutive manner. The flow lines have to be visited by assemblies resulting from a production order in a prescribed way. Some of the stations are equipped with auxiliary resources like jigs or cranes. A processing without these auxiliary resources is impossible. Vehicles to transport certain components form another class of resources. The auxiliary resources and the transportation resources are described by attributes like speed, maximum load quantities, and availability. Human resources are required to perform the production or assembly tasks. This is similar to one-of-a-kind production processes. There are buffers between the stations of a flow line and between the flow lines. Because of the huge size of some of the components of an airplane, the capacity of the buffers is often limited, i.e., usually only a small number of components can be stored there. The buffers are required to decouple the stations and the flow lines. Because of the finite buffers, a blocking of the entire flow line can occur. There are storage facilities close to the stations that are used to store components that are required to assemble the airplanes or parts of them. The storage facilities are delivered by suppliers or by the aircraft manufacturer itself. They are equipped with different inventory policies. Additional attributes including safety stock quantities and replenishment lead times have to be specified.

The system objects are derived from production orders for airplanes. The structure of each individual product is described by a bill of materials (BOM). An aircraft is assembled from several millions of parts. Thousands of assembly operations are required (cf. Scott 1994 and Heike et al. 2001). According to Scott (1994) we differentiate between the following processes

- airframe assemblies including wings, fuselage, nose
- airframe join where major assemblies are joined
- final assembly and installation where interiors, engines, and systems are installed and functional tests are performed.

Based on the BOM, each single customer order is decomposed into work packages. A certain work package corresponds to a subassembly like a wing or a nose section, to an airframe join, or to activities in the final assembly line (FAL). A work package consists of a certain set of tasks. Resources are specified in an aggregated manner on the work package level, e.g., it is known how many workers are required to assemble one wing within three days. In contrast, the tasks have to be performed using individual resources. Each task requires certain skill types of the workers. The duration of a task depends on the number of workers that are assigned to work on the task. We call this a multi-mode situation. The qualification of the workers might also have an impact on the task duration. In addition, the duration of tasks is influenced by learning curves (cf. Benkard 2000). As a result, the durations are much longer in the ramp-up phase of a product. There are spatial constraints for the number of workers that can be assigned to a specific task. The moving entities are assemblies. They are routed through the network of stations. When a joining of assemblies is necessary, the corresponding entities are combined into one entity. Routes are assigned to each part of a BOM that describe how to produce or assemble it. Note that the routes lead to precedence constraints among the work packages and the tasks. For instance, the airframe join-related work packages can only be performed after the wings and the fuselage are assembled. The work packages and tasks lead to a partial order with respect to the precedence constraints. Networks consisting of activities that are carried out on nodes, so called activity-on-nodes (AON) networks, are used to represent the BOM and the routes for each single work package. The activities correspond to tasks, while the nodes represent the resources. The assembly process has to respect the precedence constraints for the work packages and tasks. Before a task can start it has to be ensured that all the required subassemblies are available. In case of tasks that can be performed in arbitrary order, a sequence has to be determined to execute the tasks.

Table 1: Characteristics of high- and low-volume serial production.

Criterion	High-volume	Low-volume
System objects	many of them, they are often small-sized	a small number of typically large-sized objects, these objects are formed based on a large number of assemblies
Product characteristics	often commodity products or products with a relative low degree of customization, medium complex BOM and routes	highly customized, often very complex BOM and multiple routes, high degree of parallelism
Processing times	processing times of the operations depend on the specific machine where the operation is carried out	depend on skills and the quantity of the workers (multi-mode)
Degree of automation	high	often low, labor-intensive processes
Sources of complexity	flow shop or job shop-type production, many system objects	customization, many suppliers, highly skilled workforce, learning curve of the staff, spatial constraints for system objects
Resources	typically stationary, i.e. machines, small number of auxiliary resources	mobile resources, workers are important resources, auxiliary resources are important
Buffers	possible, often not a major constraint	often major constraint due to size of the system objects

Next we discuss the workforce control. While in high-volume production an operation has to be assigned to an available machine, the situation is more sophisticated in low-volume serial production. A certain number of workers are assigned to each station for a given number of shifts. One of the feasible modes has then to be chosen for each task that has to be performed next. Because a task can be longer than one shift, a preemption of tasks is possible. The main characteristics of high- and low-volume production are summarized in Table 1.

Next, we briefly summarize the main similarities and differences between low-volume mixed model assembly lines and one-of-a-kind production processes found in shipbuilding or in construction. According to Spieckermann (2011) one-of-a-kind production processes are labor-intensive. There are a large number of different possibilities to perform the production process. Different resources, some of them are mobile, are used in one-of-a-kind production processes. This is also true for the low-volume production in aircraft manufacturing. One important difference is given by the stationary production facilities in low-volume assembly lines, whereas the production facility, for instance, a building in construction, might often change over time and is not clearly determined in one-of-a-kind production. There are also different types of disturbances, for instance weather changes, in construction.

2.2 Related Work

Mas et al. (2013) discuss a conceptual design model for aircraft assembly lines. It turns out that methods and software have to be developed to support assembly line designers. The current design process in the aerospace industry heavily depends on personal experience since formal models for evaluation and decision making are not available. The effect of crew and spatial constraints in aircraft assembly operations to improve crew assignment, operation effectiveness, and cycle time is discussed in an early paper by Scott (1994). Logistics processes and disruptions in manufacturing processes are not studied in this paper. A simulation model of an aircraft assembly line based on the package Quest is presented by Lu et al. (2012). Simulation is used in this study to determine bottlenecks. Majohr and Rose (2008) propose a simulation-based heuristic to improve the workforce management for complex assembly processes as can be found in the aerospace industry. The major goal is to balance the utilization of workers across the different stations. Noack and Rose (2008) extend and refine this simulation-based optimization approach by considering slack reduction objectives. Because of the workforce scheduling objective, highly detailed models are proposed in these papers. However, the goal of the present paper is not workforce scheduling, i.e., we are not primarily interested in optimization approaches. Instead of this, we are more interested in understanding important modeling concepts of the researched domain. A specific simulator for the throughput determination in mixed-model assembly is recently proposed by Tiacci (2012). However, it seems that this simulator is not able to cope with the complexity found in low-volume assembly lines. This also applies to simulation approaches of assembly lines in the automotive industry (cf. Ulgen and Gunar 1998) where the degree of automation is higher and the lead times are much shorter compared to aircraft manufacturing.

While the previous papers are more related to detailed assembly operations, there are a couple of papers that deal with logistics and supply chain problems in the aerospace industry. We refer, for instance, to (Hermelijn, Steenbakkers, and van der Weij 2012) and (Visintin, Porcelli, and Ghini 2013). In contrast to the workforce scheduling situation, more aggregated simulation models are appropriate. However, the proposed simulation models are rather situation-specific and not unified.

Steinhauer (2011) and Steinhauer and Soyka (2012) discuss the development of simulation tools for one-of-a-kind production processes with focus on shipbuilding. Similar to an aircraft, a ship can be considered as a complex product. The Simulation Toolkit Shipbuilding (STS) is presented. It is interesting to see a description of the main building blocks in shipbuilding. The aim of the present paper is to develop a similar conceptual model for low-volume mixed model assembly lines in the aerospace industry.

Based on the discussion of related work, the goals of the remainder of this paper can be summarized as follows. First, we are interested in deriving important building blocks of simulation models for low-volume assembly lines and exemplifying their implementation using the discrete-event simulation tool AutoSched AP. This tool is a highly customizable framework coded in the C++ programming language (cf. Applied Materials 2014). The second goal consists in applying these building blocks in a specific case study that is based on a real-world problem found in a FAL of an aircraft manufacturer.

3 BUILDING BLOCKS OF SIMULATION MODELS FOR ASSEMBLY LINES

3.1 Modeling of Products and Resources

The different product models are represented by individual parts with specific routes describing the production and assembly tasks, their durations, and precedence constraints. Single steps of the route are linked to an individual BOM in AutoSched AP. In addition, subparts for the assembly processes are required. They are defined as parts that are used for assembly processes according to the BOM. A route for each subpart of the BOM with precedence constraints among tasks is specified. The assembly tasks are the final step of the route where the subparts are joined into an assembly entity.

Routes are modeled on the task or the work package level according to the required granularity. On the work package level, the resources and steps in the route are aggregated in an appropriate manner. Individual resources for detailed steps with required skill types for workers are defined on the task level. Alternative routes with an aggregated representation of tasks are used to model tasks that can be processed in parallel. The same concept can be applied to model the multi-mode situation.

Because human resources are required to perform production or assembly tasks, workers and their skills have to be modeled. The granularity has an impact on the workforce control. Workers are represented as worker classes on the work package level while specific skills for small groups or single workers have to be specified on the task level using the certification attribute of operators in AutoSched AP. In addition, the qualification of workers is modeled by the operator efficiency functionality. Information about the availability of the resources as a consequence of shifts, failure, and down times is required. The required behavior is modeled using shift and down calendars with mean time to failure (MTTF), mean time to repair (MTTR), and the corresponding probability distribution of AutoSched AP. Operator calendars are used to align the station availability to the shifts and to model the preemption of tasks. It is a common approach to model only the segment of the production system and process which has to be studied. However, because this specific segment is also influenced by external entities or by upstream stations, we consider an artificial station to model this behavior. MTTF and MTTR parameters can be specified for this station to represent delays in the overall process caused by upstream stations.

3.2 Modeling of Suppliers and Storage Facilities

External deliveries by suppliers are characterized by minimum and maximum possible quantities and the availability and speed of the corresponding transportation vehicles. As a consequence of the large-size production facilities, vehicles for internal transportations between stations have to be modeled. They are modeled as resources that form a batch of jobs for delivery. A batch in AutoSched AP is a collection of jobs that are processed at the same time on the same resource. Each batch requires a minimum number of jobs to form it. Since this minimum quantity might change over time, we will use the blackboard-type data layer from (Mönch, Rose, and Sturm 2003) to represent the batches. The data layer contains important business objects and their state to avoid a heavy customization of the AutoSched AP framework. The objects of the data layer are updated in an event-driven manner by notification functions of the simulation engine. The data layer is a set of classes coded in the C++ programming language. These classes are extended and refined to fulfill the domain-specific requirements of simulation models for low-volume mixed model assembly lines.

In some situations, storing of parts on a station with assembly processes is not possible because of the huge size of some of the assembly components and the finite station and buffer capacities. It is possible that a delay causes a longer occupation of such a station by a production job whereas the delivery of subparts for the subsequent job is already initiated and the subparts arrive at the station. On the one hand, a buffer for subparts close to the station is modeled. The buffer allows the vehicles to unload after the transportation in case of a station that is occupied by a previous job. On the other hand, blocking is a typical situation in the aerospace industry. A station is blocked if the current job is not completed or the already completed job cannot be transferred to a downstream station. The Kanban extension of AutoSched AP is utilized to model this behavior. Kanban cards are applied at stations. Each station has exactly one card linked to the current job that is processed at the station. The card is used to block the station if the current job is uncompleted or the already completed job cannot be transferred to a downstream station.

Storage facilities are modeled as resources with a hold factor for subparts to be deactivated for a certain portion of entities by an information flow implemented in the data layer indicating a withdrawal. If an inventory withdrawal from a storage facility is initiated, the required quantity of subparts according to the corresponding BOM is released if available. The withdrawal is implemented in the data layer. In addition, the storage facilities are equipped with different inventory policies, i.e., attributes including safety stock quantities, replenishment lead times, and reorder quantities are used to characterize the policies. A replenishment of a certain quantity is initiated at certain points of time. The decision to initiate a replenishment activity considers the inventory position. The inventory position is the sum of the inventory level and the already ordered, but not yet arrived inventory while the inventory level is the difference of the inventory on hand and the backlog. A stock counter representing the inventory level and position can be used to make a decision for a new replenishment. The counter is checked each time a withdrawal takes place. A replenishment of new parts can be initiated, for instance, in case of an inventory level less than a reorder point of the storage facility. Additional AutoSched AP attributes are implemented for each storage facility to represent the reorder quantity and point. The reorder quantity describes the quantity of replenished entities and the reorder point the safety stock quantity where a replenishment of new entities is initiated. They can be used in the data layer for the implementation of different inventory policies.

Replenishment parts are converted into subparts if arriving at the storage facility to ensure a detailed traceability of the simulation elements (cf. Lu et al. 2012), i.e., for instance, it is important to distinguish a replenishment part from a subassembly part in cycle time statistics. A storage facility withdrawal is initiated by a production job that belongs to a product model unit. Each product model unit is described by a unique manufacturer serial number (MSN). Withdrawn subparts are assigned to the jobs and labeled with the same MSN in the data layer.

The subparts are distinguished in standard parts following a Make-to-Stock (MTS) strategy and customized parts based on a Make-to-Order (MTO) policy. Standard parts are identical in each aircraft and are held in a storage facility whereas customized parts are selected by the customer and delivered Just-in-Sequence (JIS), i.e. directly forwarded to the assembly line. Dependencies between processes or internal supplies are possible (cf. Lu et al. 2012). For instance, different parts provided by internal suppliers require a Just-in-Time delivery at assembly stations to ensure an almost simultaneous arrival. The information flow initiating such deliveries is implemented in the data layer and initiates the release of parts at certain points of time. The AutoSched AP statistics are extended to allow an analysis of the inventory policy, i.e. the time of reorders including the reorder quantity and the inventory position are gathered.

For the sake of completeness, we briefly summarize the remaining settings that are required to model and simulate aircraft production processes. An initial inventory level for each storage facility has to be specified to avoid delays due to empty storage facilities at the beginning of the simulation. Incoming jobs from upstream stations are represented by standard order files of AutoSched if only a certain segment of the production process is modeled.

4 CASE STUDY

4.1 Problem Description and System Design

The described building blocks are applied to model and simulate the cabin installation process that is based on a problem found in the FAL of an aircraft manufacturer. The modularity of cabin components is increased using a new conceptual design of the supply network for a future aircraft program. It is possible to preassemble selected components before they are assembled in the FAL. We are interested in analyzing how suppliers can support the new concepts by changing reorder quantities and frequencies to reduce the supply chain-wide inventory and increase the throughput. Due to the sources of randomness, simulation is appropriate to understand the behavior of the system.

Four single aisle (SA) aircrafts, i.e. four different product models, each with an individual route and BOM and three subparts, called components, produced by independent suppliers are considered. Component 1 is a highly customized and expensive overhead stowage compartment. Consequently, it is produced in a MTO manner and follows a JIS policy. Component 2 is a Passenger Service Unit, whereas component 3 is an oxygen box. They are standard parts which are produced following a MTS strategy and stored into storage facilities.

The considered section of the cabin installation process is characterized by a preassembly sequence with four preassembly stations for component 1 and 2 and three different stations of the FAL which are denoted by FAL 1, FAL 2, and FAL 3. FAL 1 and FAL 2 are assembly stations for component 1+2 and 3, respectively, while FAL 3 is the test station of the cabin intercommunication data systems. The routes of component 2 and 3 consist of supplier production and transportation, the storage facility, and the transportation to the preassembly and FAL 2 buffer, respectively. Component 1 is forwarded to the preassembly station after the delivery by the supplier, preassembled with component 2, and transported to the FAL 1 buffer. We use a triangular distribution for the processing times at the three FAL stations. These processing times represent the real-world situation. Learning curves are not considered. For the sake of simplicity, the remaining processing times are assumed to be deterministic. The layout of the system is shown in Figure 1.

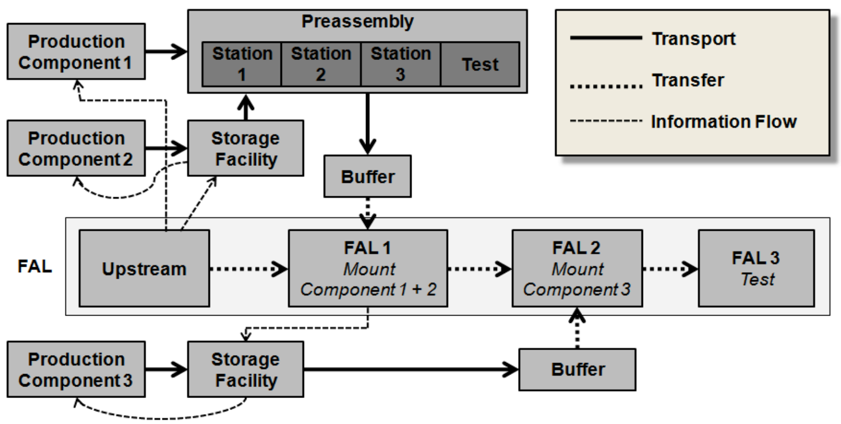

Figure 1: System layout.

Each storage facility requires a reorder quantity and a reorder point. We apply the $(s, n \cdot q)$ inventory policy for the two MTS components where s is the reorder point, q is the reorder quantity, and n is a positive integer. The inventory position I_t^d is checked each time components are removed from stock or delivered. If I_t^d is less or equal to s at the review time t then the quantity $n \cdot q$ is ordered. After replenishment, the inventory position is between s and $s+q$, i.e., the actual ordered quantity is the product of n and q calculated dynamically such that the condition

$$s < I_t^d + n \cdot q \leq s + q \tag{1}$$

is fulfilled. In the researched setting, the supplying nodes are external suppliers who fulfill orders after the replenishment lead time. We assume that we cannot influence the reorder quantity q because this is a result of the capacity of the transportation devices of the suppliers. A low, moderate, and high reorder quantity q of 60, 120, and 240 are considered.

The arrival of components at the assembly stations has to be synchronized. In particular, the order points of the components represented by the information flows in Figure 1 are set accordingly. The production of component 1 and the transportation of component 2 are initiated some time before they are needed at station FAL 1. A station called Upstream serves as the order point for component 1 and initiates stock withdrawals of component 2. The transportation procurement of component 3 for station FAL 2 works similar as explained for component 2.

The internal deliveries of components to FAL buffers are restricted by batch sizes corresponding to the number of required components to be assembled into the aircraft defined in the BOM. An aircraft can only be transferred to a specific FAL station if the station is idle because of buffer space constraints. Otherwise, a blocking occurs at the upstream FAL station.

Both the preassembly and the FAL stations require workers to perform the assembly tasks. The workers available in the preassembly line are allowed to work on each preassembly station while workers of the FAL are assigned to specific stations because of skill reasons. For the sake of simplicity, we assume that the First-In-First-Out (FIFO) dispatching rule is applied at the stations and by the resources. A two-shift pattern is used for the worker availability. One shift has eight hours. The availability of stations and vehicles is set to 16 hours using operator calendars.

In addition to the order point functionality of the station Upstream, this station is used to model disruptions in the upstream processes. A down calendar is specified. Down calendars are also defined for the workers and for the production at supplier site to simulate delivery disruptions. We consider different disruption scenarios at the production and the supplier site. The disruptions might lead to delays in the production process caused by late modifications, rework, a higher workload for new items, and missing parts. We expect that the stochastic behavior has an impact on the performance. Two sources of uncertainty are considered. The first one is a delay d in the arrival process of aircrafts in the FAL. On the one hand, we have highly frequent delays with a small duration, i.e., every third aircraft has a delay that is taken as a realization of the random variable $X \sim U[10.8,13.2]$, where $U[a,b]$ denotes the uniform distribution over $[a,b]$. This means that the mean is 12 hours. We also consider delays with rare frequency and long durations. Every sixth aircraft has a delay that is taken from $U[21.6,26.4]$, i.e., the mean is 24 hours. The two settings are denoted by $d=(3,12)$ and $d=(6,24)$. We also analyze the impact of the supplier reliability f as a second source of uncertainty. Delays in the deliveries of the three components may occur. We consider a moderate setting and a setting with a more reliable supplier. In the first case, the durations of the delays follow $U[1.8,2.2]$, i.e., the average duration is two hours, whereas the delays happen on average every two days, i.e., the occurrence is taken from $U[1.8,2.2]$. The more reliable setting is characterized by durations that are taken from $U[0.9,1.1]$ whereas the occurrences follow the distribution $U[3.6,4.4]$. We abbreviate the two settings by $f=(2,2)$ and $f=(4,1)$, respectively.

A constant SA product mix of 3:1:1:1 is assumed. We consider two different release rates r because we expect that a higher utilization leads to a larger impact of the inventory management. A target throughput of 78 aircrafts within the simulation horizon is reasonable for the new product architecture. Furthermore, we consider a moderate utilization case that is given by releasing 66 aircrafts. The initial inventory level of component 2 and 3 is 360 and 500, respectively. The 24 scenarios are summarized in Table 2.

Table 2: Design of experiments.

Factor	Level	Count
r	66, 78	2
d	(3,12), (6,24)	2
f	(2,2), (4,1)	2
q	60, 120, 240	3
Total number of scenarios		24

We simulate 210 days. A warm-up period of four weeks is chosen to exclude initialization effects. As a result, a simulation horizon of 182 days is used to compute the performance measure values. Note that we simulate five independent replications of each scenario to obtain statistically reasonable results. The performance measure values are the average of the values for the different replications.

We are interested in the impact of the inventory management for the two MTS components on the throughput of the FAL. We change the reorder points s of component 2 and 3 to compute appropriate parameters for the $(s, n \cdot q)$ policy. Binary search is used to determine appropriate reorder points. A minimal value of $s = 100$ and maximal value of $s = 500$ is used to start the binary search. The setting $s = 500$ leads to the maximal possible throughput in each scenario, while $s = 100$ leads to throughput losses. We increase the reorder point if the throughput decreases and decrease it as long as the throughput remains constant. We start the binary search for the reorder point of component 2 while choosing a reorder point of 500 for component 3. We then move the binary search for the reorder point of component 3 while considering the selected reorder point for component 2. Note that the sequence of considering the two components in the binary search procedure does not lead to significant differences in the parameters found. Around 15 iterations are necessary. We show some appropriate parameter settings found by the binary search procedure for a specific scenario in Figure 2.

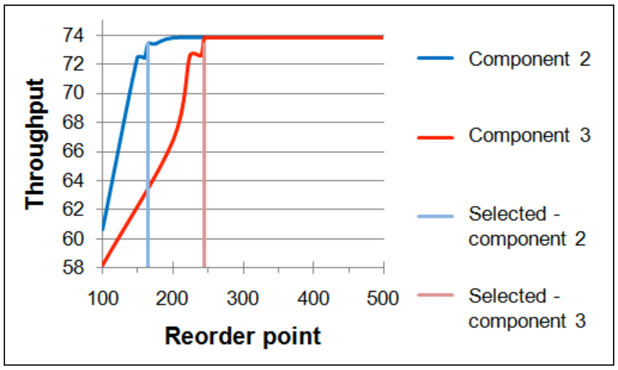

Figure 2: Reorder point – throughput curve.

The AutoSched AP statistics extension for the inventory policy parameters is used to reduce the inventory on hand, while maintaining a high throughput. The performance of the system based on the new conceptual design is assessed using the throughput ρ of the FAL and the time-weighted average inventory on hand $\tilde{I}_2^p$ and $\tilde{I}_3^p$ of component 2 and 3, respectively.

4.2 Simulation Results

The impact of the selected reorder point and quantity on the throughput is investigated. To show the relation between reorder point and quantity and the performance measures, we analyze the selected reorder point for each component and the corresponding throughput given in Table 3. We obtain almost the same ρ for moderate and high values of q and larger values of s_2 and s_3 for lower values of q in most situations. For low values of the reorder quantity, the throughput is lower and the reorder point is larger compared to the corresponding values of higher reorder quantities.

Next, we investigate the impact of the system variability d. In the case of high utilization, the throughput is larger for frequent delays with small duration. In contrast, we get a smaller value for ρ in case of a moderate utilization. We obtain similar results for the supplier reliability f. More reliable suppliers lead to higher throughput in case of a moderate utilization whereas the throughput decreases for a high utilization.

Very low reorder quantities lead to a small inventory on hand. This can be seen when we look at the time-weighted average inventory on hand values in Table 3. Figure 3 exemplifies the inventory on hand and the inventory position of component 3 for a certain portion of the simulation horizon. Here, a scenario with $r = 78$, $d = (3,12)$, $f = (2,2)$, and s_2 and s_3 values determined by the binary search procedure for low, moderate, and high reorder quantities, respectively, is simulated. Using low reorder quantities, the inventory on hand is often zero and backlog occurs. These effects are much smaller in case of moderate and high reorder quantities as can be observed in Figure 3.

The simulation results indicate that high reorder quantities and large values for the reorder points do not cause any problems with respect to the throughput ρ, but the time-weighted average inventory on hand is large. This effect is more visible when we consider scenarios with high utilization. A lower reorder quantity is compensated by an increased reorder point. If the reorder points are too small then large throughput reductions are the result. Therefore, it is more important to select appropriate reorder points and quantities in case of a highly utilized system.

Table 3: Simulation results for the scenarios.

d	f	q	$r = 66$					$r = 78$				
			s_i		ρ	$\tilde{I}_i^p$		s_i		ρ	$\tilde{I}_i^p$	
			$i = 2$	$i = 3$		$i = 2$	$i = 3$	$i = 2$	$i = 3$		$i = 2$	$i = 3$
(3,12)	(2,2)	60	350	310	59.6	18.2	62.6	325	310	59.0	21.4	48.6
		120	220	145	65.2	51.5	122.5	245	190	74.0	68.5	115.8
		240	170	120	65.6	89.4	156.2	170	215	74.4	165.6	134.5
	(4,1)	60	350	320	62.6	24.1	66.8	325	120	60.6	12.9	152.8
		120	170	190	65.8	80.7	86.7	245	165	73.4	60.2	129.1
		240	170	120	66.0	95.8	161.5	170	165	73.8	119.1	139.8
(6,24)	(2,2)	60	350	430	60.2	42.3	38.7	325	370	58.6	32.9	51.3
		120	195	165	65.4	69.4	100.3	245	190	73.4	68.6	110.7
		240	170	120	65.4	92.1	161.8	170	215	73.4	163.9	129.7
	(4,1)	60	350	165	61.8	10.4	145.2	350	405	61.4	31.9	44.2
		120	170	190	66.2	81.1	77.7	245	145	72.0	51.5	131.9
		240	170	165	66.2	121.1	156.7	170	215	72.4	169.0	128.2

5 CONCLUSIONS AND FUTURE RESEARCH

In this paper, we discussed modeling and simulation aspects of low-volume mixed model assembly lines in the aerospace industry. Important domain characteristics were derived. Based on this domain characterization, we described major building blocks of related simulation models. In addition, we discussed the implementation of selected modeling concepts in the AutoSched AP simulation tool. The identified building blocks are used to simulate the cabin installation process in a FAL in the aerospace industry where we demonstrated the importance of an appropriate inventory management in low-volume mixed-model assembly lines.

There are several directions for future research. First of all, we are interested in extending and refining the building blocks for simulating low-volume mixed model assembly lines. Our ultimate goal is to come up with a rather complete simulation library similar to STS in shipbuilding. We expect that simulation models based on the library can be used to assess production plans for problems similar to those proposed by Heike et al. (2001) in a dynamic and stochastic environment taking into account disturbances caused by suppliers and by workforce availability. Moreover, it seems possible to improve the corresponding production plans by simulation-based optimization.

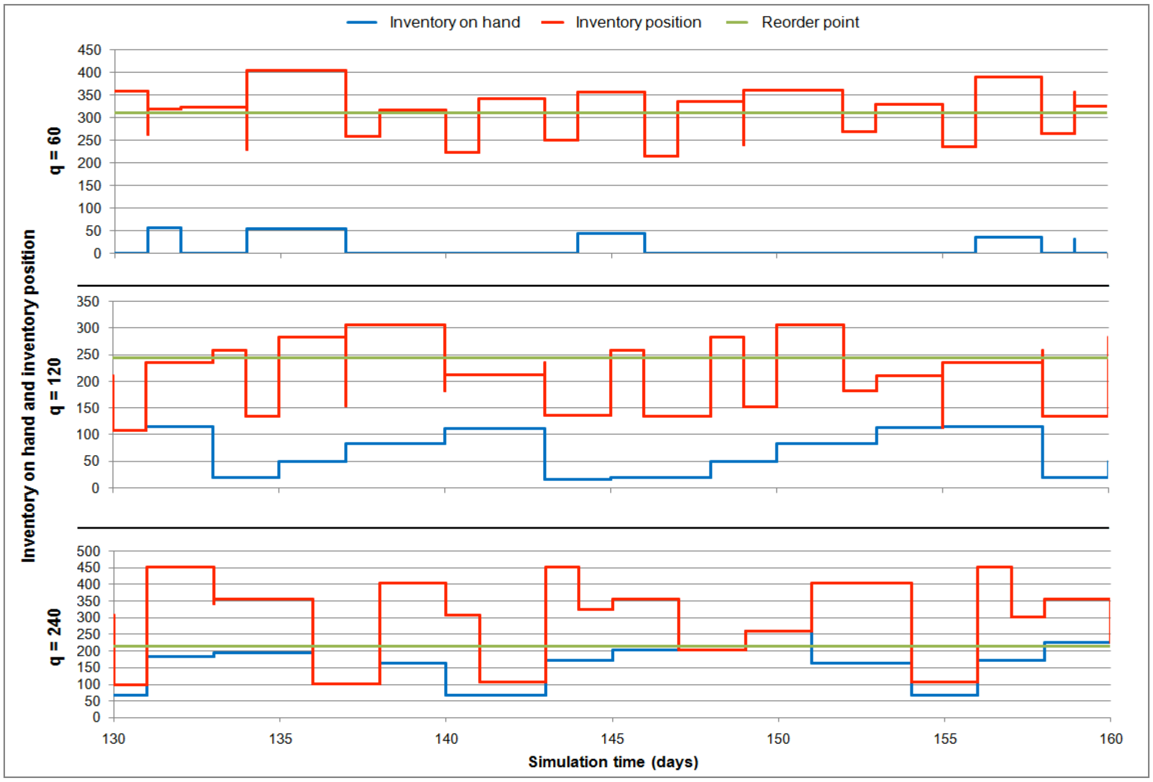

Figure 3: Inventory for different settings of q for a scenario with $r = 78$, $d = (3,12)$, and $f = (2,2)$.

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