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Logistical Control of Flexible Processes in High-Throughput Systems by Order Release and Sequence Planning

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Abstract

High-Throughput Systems (HTS) are utilised predominantly in pharmaceutical and food industry as well as medical technology. Those rigidly linked systems with large outputs of up to 100,000 samples per day are used for screening or synthesis. The usage of HTS enables major increases in quantities and decreases in throughput time. With regard of testing materials in a HTS flexible processes and process inherent restrictions have to be controlled. Currently it has not been researched whether a logistical control method which is able to deal with these requirements exist. Due to this, in this early approach the influence of order release and sequence planning in a HTS with occurring ad hoc changes like partial testing and re-routing is considered and evaluated. The results demonstrate indicators for the development of a new generation of logistical control methods which enable production systems to produce a high number of variants in high volume.

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Keywords: logistics; control; High-Throughput Systems

1. Introduction

High-Throughput Systems (HTS) facilitate tests of 10,000 to 100,000 and Ultra-High-Throughput Systems even more than 100,000 samples per day [1]. These systems are used for synthesis and screening in pharmaceutical and food industry as well as in medical technology [1-5]. For the implementation of HTS automation and robotics are mandatory. This causes high acquisition costs which are compensated by the advantages of HTS. The highest reduction of the costs can be achieved through the noticeable lower development costs and times [4] [5].

Most of conventional HTS are rigidly linked. They do not work as multi-purpose systems and execute one specified synthesis or screening. With regard to innovative, sustainable and resource-saving constructions it is necessary to use materials which possess requested characteristics. The target-oriented search of materials with defined characteristics causes a high volume of samples. HTS are suggested for finding structural material with the requested characteristics in a time and cost effective way. Testing material characteristics is a mostly iterative process that depends on the material and the requested characteristics. The identification of varying characteristics of material often has to be done with different testing procedures. The identification of structural material with specific requested characteristics in HTS is possible if every station in the system is embedded in one common logistic control method [6]. The process of testing materials is not rigidly linked as the screening in conventional HTS. Due to the target of testing more than one material characteristic there would appear flexible processes as well as ad hoc amendments. Therefore, a logistical control method is required.

The implementation of test methods in HTS could reduce the throughput time and increase the quantities dramatically. Due to the implementation of testing materials in HTS a system which is able to deal with a high variety and high volume should be achieved. In this early approach the effect on the throughput time and the average output caused by the

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application of order release and sequence planning has been simulated and evaluated.

2. Material testing in HTS

Identifying specific material characteristics in conjunction with varying material compositions may cause a high number of tests until the requested quality is achieved. The implementation of material testing in HTS enables the testing of these high volumes. Contrasting to conventional HTS, a HTS for material testing is a multi-purpose system which is able to measure different material characteristics like tensile strength and yield strength.

Schneider et al. pointed out that due to the implementation of material testing in HTS, restrictions like re-routings and partial testing have to be taken into account. Destroyed samples should not be measured. By ad hoc skipping these scrap the throughput time and the costs could be reduced, especially if high rates of scrap appear. Measured sample properties can influence the further testing process. On the basis of specific measurement results it can be necessary to re-route the test plan. These ad hoc re-routings can affect the subsequent testing sequence or single testing stations. One kind of ad hoc re-routing which impacts one testing station will occur if a measurement is incorrect. In this case the samples have to re-run the station for a retesting [6].

In contrast to conventional HTS, HTS for material testing requires high process flexibility as shown in table 1. Especially the varying process sequences and the undirected material flow lead to a high complexity with regard to the control of the system.

Table 1. characteristics of HTS.

characteristic	conventional HTS [1-5]	HTS for testing material characteristics [6]
material flow	directed	undirected
sample type	uniform	variable
amount of inspection	unique and complete	repetition check and skipping of damaged samples
process sequence	static	varying according to: • sample type • aim of analysis • test result

3. State of the art

Testing materials in HTS is an innovative approach. The effect of re-entrants in production systems which are similar to re-run one or more test stations was detected by Seleim and ElMaraghy. Their analysis of manufacturing systems showed that depending on its parameters simple re-entrants could have major impacts on the whole system. Due to this fact it is important to understand the dynamics of a production system with re-entrants. Especially if a system with re-entrants is a subsystem of a larger production system. In this case the output of the subsystem is the input of the other system. Through this the re-entrants influence following production steps as well [7]. Schneider et al. investigated the influence of partial tests and ad hoc re-routings including retesting in HTS for material testing [6]. These first simulations in a simplified environment show an increase of the throughput time of up to 23 % caused by retests and a decrease of up to 20 % caused by partial tests [6].

With regard to current literature, no logistical control method has been found, that is able to deal with the specific requirements of HTS (table 1).

There are existing approaches for the usage of workload control in job fabrication with high routing complexity but these apply on low quantities [8]. This paper shows a first approach for the enabling of logistical control of high volumes and high number of variants.

4. Logistical control method for testing materials in HTS

As described in section 2 the intended HTS has ad hoc varying processes like skipping of scrap and re-routing. Due to the fact that currently no logistical control method is able to deal with this complex processes a new logistical control method has to be developed.

The described versatility of the products in the purposed HTS for material testing is similar to job shop production as showed in table 2. Both show variable and recursive material flows as well as flexible process chains that depend on the request. In contrast to the job shop production the recursive material flow and the skipping of scrap are standard processes in HTS for material testing.

Table 2. similarities and differences comparing job shop production and HTS for material testing.

characteristic	job shop production	HTS for testing material
material flow	undirected	undirected
process chain	depending on order	depending on order
variety	high	high
re-routing	rare case, should be avoided	common, standard process

Due to the structural similarities between job shop production and HTS for material testing the influence of the option of using Decentralised Work in Process-oriented Manufacturing Control (DEWIP) as an element within the development of a new production planning and control algorithm has been evaluated.

The DEWIP by Lödding is based on a control loop between working stations before orders are released. This allows the integration of production´s workforce in the responsibility of achieving logistic targets. Every working station has a work in progress account in which upcoming orders are listed. Orders will be released if the following working station has not reached the limit of its account. The sequence in which the orders are proofed for release is built in accordance to the urgency of the orders. The sequence planning is the connection between the production planning and the DEWIP [9].

The described logistical control method has been modified for the usage in the HTS. Instead of sorting with regard to the urgencies, the orders are sorted by a variation of the well-known First-in-First-out (FiFo) sequence planning, which is called First-in-System-First-out (FiSFo). This sorting composes the sequences regarding their entrance into the system [10]. Due to this, the changes in the order sequence which are caused by the DEWIP could be reversed by FiSFo. The conventional FiFo sorting with regard to the entrance in one working system is unable to interchange those alteration of the sequence. Furthermore, the sorting via FiSFo avoids that orders are passed at one working system by orders which entered the system later.

5. Simulation

Assumptions which were made for the design of the simulation model are explained below. Essentially the model is built on an exemplary HTS for testing material properties. The stations and processes which are implemented in the simulation model as well as their properties are explained in section 5.1. The simulated scenarios are specified in section 5.2.

5.1. Simulation settings

The simulation is implemented in the simulation environment Plant Simulation. For an exemplary reproduction of testing materials through HTS the following working steps are applied. The workflow is shown in figure 1 and consists of sample generation followed by fixation of samples on two different kinds of carriers, three possible treatments of the samples, six different testing stations and a final archiving. After the generation of the samples they are fixated on a carrier and would be treated as basis for the testing stations or passed on directly to the test. In the simulation model there are two stations for mechanical treatments and for heat treatments. Due to these treatments the structure and the form of the samples are changed. The formal and structural changes are measured in the testing stations and indicates the material characteristics. Several stations of the system need different carriers. Due to this it could be necessary to change the carrier. In this case the samples have to pass the fixation again. On both kinds of carriers 25 samples can be fixated. The samples are guided through the HTS via a test plan. The generation of these test plans depends on the requested material characteristics, of which seven can be analyzed by the HTS. For testing those characteristics, working steps are defined as shown in table 3. According to table 3 testing plans are generated for every expected characteristic. Due to the fact that some of the testing stations destroy the samples, testing queues of two to three working steps are composed during the simulation. Test 1, test 3, test 5 and test 6 are destroying tests. The requested material characteristics are provided on a preassigned list. On the defined points in time the orders from the list with the material characteristics are triggered in the HTS.

Table 3. Material characteristics and needed working steps (WS) for testing the characteristics.

material characteristic	WS 1	WS 2	WS 3	WS 4	WS 5
characteristic 1	test 2	test 6	test 1	test 4	test 5
characteristic 2	test 1	test 5			
characteristic 3	test 5				
characteristic 4	test 6	test 4	test 1	test 5	test 2
characteristic 5	test 6	test 4	test 1	test 2	
characteristic 6	test 3				
characteristic 7	test 5				

According to the order and the requested material characteristics, experimental designs are generated and the orders are divided into production orders.

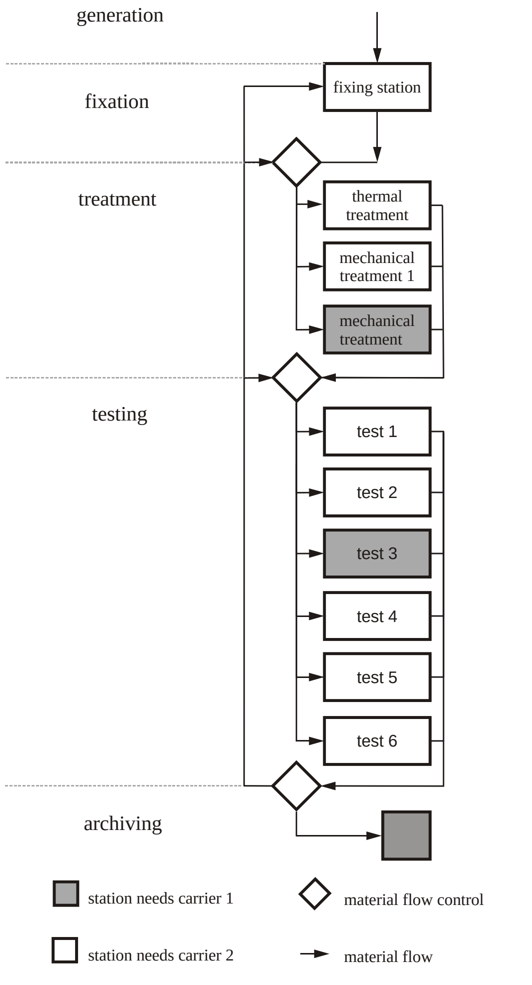

Fig. 1. Structure of the simulation model.

Based on the orders the plans are generated and released in accordance to the scenario as described in section 5.2.

Every station in the production system has a buffer. If a buffer reaches its limit, it will be unable to take in the upcoming orders. Due to this previous production are blocked and cannot process the next order. Samples which have to be retested cannot block the system because there are reserved places in the buffer. This prevents a complete blockade of a working system. In the simulation it is assumed that every buffer can store 13 trays from which nine are reserved for retests.

5.2. Simulation scenarios

Table 4 lists all simulated scenarios, which are necessary to evaluate the influence of order release and sequence planning on ad hoc adjustment of processes. These ad hoc adjustments include retests and partial tests. With regard to the conventional rigidly linked HTS the effect of the logistical control method is assessed by the scenarios 2, 4, 6 and 8. In scenarios in which the DEWIP is not used (scenarios 1, 3, 5 and 7), the orders are released directly and are sequenced according to their entrance in the working system (FiFo). It is expected that this control method corresponds closely to conventional HTS, in which the working stations are rigidly linked. With regard to the appearance of ad hoc adjustments, the occurrence of partial testing and retests are simulated. In scenarios with occurrence of retests it is supposed that an incorrect measurement appears, which effects the retests. Furthermore, it is assumed that the appearance follows the normal distribution with an expected value of 100, a standard deviation of 10 and an upper threshold of 120. Through this 2.7 % of the samples are retested. The samples have to pass the relevant working station again. Those retests are listed on the account of the station and are released by the DEWIP again. Furthermore, damaged samples are not tested again. In this case a partial testing of the carrier is performed by skipping the scrap. The appearance of damaged samples is also normal distributed. In this case an expected value of 100, a standard deviation of 20 and an upper threshold of 120 is expected. Due to this 84.1 % of the samples are not skipped in the testing stations. The processing time decreases for carriers with damaged samples with regard to the number of those.

Table 4. Simulated scenarios.

scenario	order release	retests	partial tests
1		x	x
2	x	x	x
3			x
4	x		x
5		x	
6	x	x	
7			
8	x		

x = appears in the scenario

These eight scenarios are simulated with three different configurations in the following simulation runs:

- Simulation run 1: This first simulation run is the basis simulation. One bottleneck station appears which causes low capacity utilizations and blockades of upstream working stations in the simulation run.
- Simulation run 2: In the second simulation run the bottleneck station was doubled. All other configurations are not changed. Due to this doubled bottleneck station the capacity utilization increases.
- Simulation run 3: In this third simulation run the bottleneck station is doubled as in simulation run 2. Furthermore, the inflow sequence of orders is faster.

6. Results

For the evaluation of the influence of the order release in conjunction with FiSFo the throughput time, the appearing blockades in the system and the average output are considered.

The results in the three simulation runs show that the order release has a significant influence on the throughput time. The generated decreases are shown in the figures 2, 3 and 4. In all simulation runs the appearance of retests (scenarios 5 and 6) causes an increase of the throughput time compared to the scenarios without ad hoc adjustments (scenarios 7 and 8). In addition, the appearance of partial testing leads to major decreases of the throughput time (scenarios 3 and 4) comparing to the other scenarios. With regard to the scenarios 1 and 2 the decreases which are indicated by the partial testing compensate the increases that are caused by the retests.

Regarding the simulation run 1, the implementation of the order release causes decreases of the throughput time from 90 % to 96 %, as depicted in figure 2.

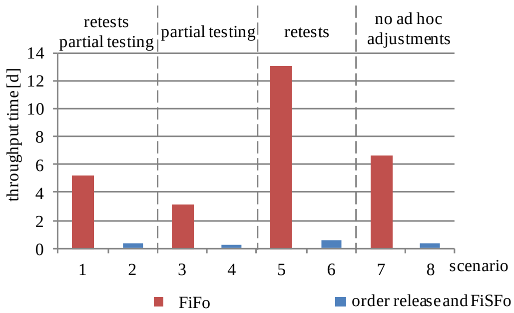

Fig.2. Throughput time of the first simulation run.

Comparing the figures 2 and 3 it is noticeable that due to doubling of the bottleneck working system the throughput time generally decreases. In the scenarios 2, 4, 6 and 8 in which the order release is used the decreases vary from 32 % to 39 %.

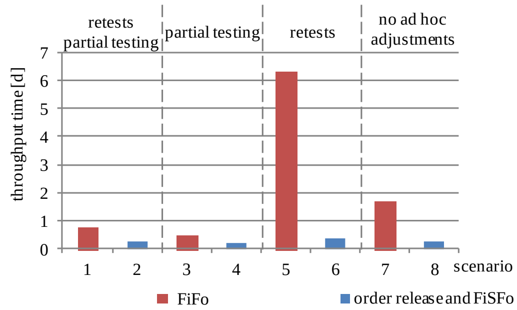

Fig.3. Throughput time of the second simulation run.

The decreases are higher in scenarios which use FiFo (scenario 1, 3, 5 and 7). In these cases, the throughput time is 51 % to 85 % lower. The doubling of the bottleneck station results in a decrease from 35 % to 85 % of the throughput time, as depicted in figure 3. This shows that the balancing of the capacity generates higher capacity utilization. The measured capacity utilization of the working systems confirms this observation.

Caused by the faster sequence of order inflow in simulation run three the throughput times increase predominant compared to the throughput times of the second simulation run. In scenario 1 and scenario 3 the throughput time is four-fold to five-fold higher. This shows that the system is stressed by the faster sequence of the order inflow. The results of the throughput time show that due to the order release the stocks in the HTS are regulated. This allows the system to execute every order on time and leads to noticeable shorter throughput times.

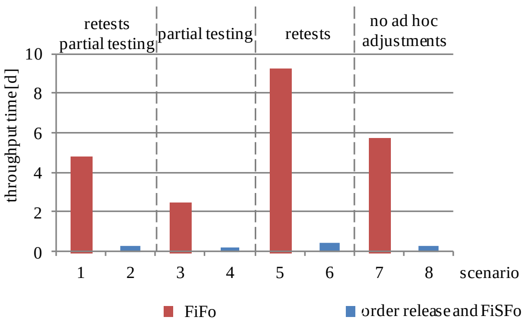

Fig.4. Throughput time of the third simulation run.

Blockades appear in scenarios in which FiFo is used only. The percentage of the blocked production time is listed in table 5. Comparing the percentage of the production time that is blocked in simulation run 1 and 2, the results support the conclusion that through the doubled bottleneck station the utilization of the capacity increases.

The order release in conjunction with FiSFo releases orders which can be processed only. In these scenarios no blockades appear.

Table 5. Blockades as percentage of the working time of the working stations in scenarios without order release.

working station	simulation run 1	simulation run 2	simulation run 3
heat treatment	44 % - 57 %	6 % - 34 %	17 % - 29 %
test 1	1 % - 47 %	2 % - 25 %	16 % - 31 %
test 3	35 % - 47 %	1 % - 8 %	3 % - 6 %

The influence of the order release in connection with FiSFo on the average output is listed in table 6.

Table 6. Influence of the order release on the average output.

scenario	simulation run 1	simulation run 2	simulation run 3
1 → 2	-1 %	-4.2 %	-8.1 %
3 → 4	+0.6 %	+1 %	-2.5 %
5 → 6	+1.1 %	+2.6 %	-5.9 %
7 → 8	0 %	+3.5 %	+6.7 %

The changes of the average output in the third simulation run (table 6) indicate that the order release is unsuitable for the usage in production systems which are stressed through a fast inflow of orders. In the first two simulation runs the results of the scenarios 1 and 2 lead to the assumption that the order release in conjunction with FiSFo is not able to deal with both ad hoc adjustments at once, as the average output decreases. With regard to the scenarios in which only one ad hoc adjustment of the testing plan appears there are mean increases in output. Furthermore, the results show that in scenarios in which partial tests and retests appear the order release causes a constant decrease of the average output.

The constant increase of the average output of the scenarios 7 and 8 show that without the ad hoc adjustments the limit of the capacity of the system is not reached. Furthermore, in scenario 8 of the third simulation run appears the highest blockade of test 1. This indicates that affected by the order release the blockades could be transferred into productive time. Due to the configuration of the scenario 8 this will be achieved if no ad hoc adjustments occur.

The average output decreases by 39 % to 66 % through the doubling of the bottleneck working station in simulation run 2 as depicted in table 7.

Table 7. Percentage of the alteration of the average output.

scenario	simulation run 1 to run 2	simulation run 2 to run 3
1	+59 %	-6 %
2	+54 %	-10 %
3	+39 %	+12 %
4	+39 %	+8 %
5	+59 %	+5 %
6	+61 %	-4 %
7	+60 %	-3 %
8	+66 %	0 %

Due to the fast sequence of order inflow in the third simulation run, the changes of the average power comparing to the second simulation run are indifferent. Increases appear as well as decreases. The decreases show that in scenario 1, 2, 6, and 7 the system is stressed by faster inflow of the orders.

The partial testing leads to a lower workload. Caused by skipping of scrap there is a reduction of the duration of the testing. This is the reason for the raised average output in the scenarios 3 and 4. This leads to the assumption that the faster sequence of the order inflow does not stress the system in these scenarios. The changes of the average output from simulation run 2 to run 3 of the scenarios 5 and 6 show how the different logistical control methods could deal with retests in a stressed situation. Due to the usage of the order release in case of occurring retests less orders are released through the system. This causes the decline of the average output. The throughput time is 13 % higher in this case. The rise of throughput time in case of using FiFo is with 46 % more intensive. This indicates that there is a higher stock in the system. Due to this the retests lead to a higher average output.

7. Summary and outlook

Until this first approach the usage of order release in HTS has not been researched. The results show that through the order release in conjunction with FiSFo major decreases in the throughput time can be achieved. Furthermore, the results show that through the release of the orders the blockade could be avoided and the average output can be increased. It indicates that in scenarios in which one ad hoc adjustment appears, the order release is able to avoid the blockade of the system. The results of the third simulation run lead to the assumption that in case of a stressed system FiFo leads to preferable results comparing to order release and FiSFo with regard to the average output. It indicates that in this situation the higher stock in the HTS generates higher outputs.

For the verification of the results further investigation is needed. The configuration of the simulation model has been changed during the studies as described in 5.2. In further investigation the influence of the configuration of the order release has to be examined. The method of the sequence planning or the limit of the WIP can be changed for example.

It is obvious that the size of the buffer has an influence on the blockades in the HTS. Due to the fact that the intended HTS will be a highly automated system there would be a fixed number of buffer places. According to this it is especially important to avoid blockades in the system with regard to the possibility of a high number of retests. If there are a high number of retests it will be possible that the system blocks itself completely. Due to this the size of the buffer is of high importance and there is need for further investigations. Regarding the influences of the two different logistical control methods the order release avoids blockades in the system and the FiFo enables higher average outputs in a stressed system situation.

In addition to the ad hoc adjustments in testing plans the influence of temporary clocked systems and the necessary changes in the logistical control method have to be researched. Generally, the intended high output could only be achieved with a logistical control method that is able to use as much capacity as possible without blocking the system.

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