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Quantification of a System Dynamics Model for Optimized Failure Management in Manual Assembly

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Abstract

Companies have only limited resources to carry out value-adding activities. In order to achieve high quality requirements, the goal-oriented and efficient handling of failure incidents is a competence that must be emphasized. However, the activities associated with this represent an additional effort that consumes part of the resources available. For this reason, it is important to optimally coordinate the value-adding processes of service creation on the one hand and the processes of failure management on the other. Accordingly, the objective of this paper is to program a simulation model for an optimized failure management in manual assembly, which transforms the failure management from traditionally experience-based to model-based. To achieve this objective, the consideration of the interactions between the failure management process and operational activities during the production process is essential. However, in current literature, interactions between production and failure management still lack detailed descriptions. Thus, both disciplines are often considered and optimized in isolation. Therefore, an advanced System Dynamics Model representing manual assembly processes with 23 elements involved is constructed and applied to indicate the interactions between production and failure management. This enables the optimized configuration of the failure management activities depending on the circumstances to be taken into account. According to the generated model, a generic process module is programmed and test runs are performed to assess the model behaviour's plausibility. The programmed System Dynamics model is implemented and validated in a use case of a manual assembly line consisting of two assembly stations. For this purpose, the generated process model is linked to the production chain of the use case and parameterized accordingly. This procedure demonstrates that the model can be used to derive general recommendations for action in order to realize an optimized design of failure management activities.

Keywords

Failure Management; Failure Handling; Manual Assembly; System Dynamics

1. Introduction

Manufacturing companies face the constant challenge of increasing quality requirements, shortened product life cycles and cost-efficient production. A major force influencing the achievement of quality, time and cost targets is the occurrence and respective handling of failures. Reference processes for the long-term elimination of failures are widely established and single steps for handling a failure are well known [1]. One problem with these processes is that they are usually designed without taking into account the interactions with the actual value adding processes. Despite the close connection between these two domains, failure

management activities are often defined and optimized in isolation [2]. Thus, it is not considered which positive or negative consequences a failure management process can have for the company as a whole. This circumstance is to be considered critically, since a conflict of objectives can exist between medium to long-term oriented failure management activities and short-term oriented production objectives with regard to the use of available resources [3]. Consequently, in order to optimize failure management, the reciprocal influence of failure prevention and product manufacturing must be taken into account. According to these thoughts, the development of a simulation model for the derivation of recommendations is described in the following. The objective is the effective and efficient integration of the failure management process into the production regarding a use case of manual assembly. Here, the hypothesis is followed that recommendations for action can be derived on the basis of a System Dynamics model. Using simulation analyses of a real assembly chain, recommendations for optimizing failure management, i.e., measures for better networking of a company's failure management strategy with its production planning and control, are derived taking into account company-specific factors.

2. State of the art

Failure management is an essential topic for manufacturing companies. Reduction of diverse types of failures during production is the critical key to achieve a better performance of a manufacturing company [4]. The concept of failure management in the manufacturing domain includes all measures for the sustainable avoidance and prevention of failures to ensure the success of production [5]. Concerning the timing of activities along the production value chain, the existing approaches for failure management can be divided into preventive methods and reactive methods. Preventive methods aim at the prevention of failure before occurrence. One of the most well-known methods is FMEA (Failure Mode and Effects Analysis) [6]. It is applicable for product design and product manufacturing, and it aims to anticipate possible failures during the manufacturing of the product under consideration. In contrast, reactive failure management is only used when failure avoidance is no longer possible, and the failure has already occurred [7]. There are various methods that describe how to deal with these failures. As we mainly aim at a model-based management of occurred failures in production domain – particularly manual assembly – and enabling manufacturing companies to learn from their existing failures, reactive failure management methods are of high importance and will be considered in the following analysis. Simulation, data modeling and many other approaches already exist in order to make the internal failure management during production process as effective and efficient as possible. Various approaches for reactive failure management are introduced by different authors.

ELLOUZE developed SAFE to support producing companies in applying reactive measures to eliminate failures that have already occurred [8]. This failure management approach includes methodological support for workers. The aim is to transmit the necessary information to the right worker at the right time in the right place. The core of this approach is to establish comprehensive and systematic storage of failure knowledge. The knowledge can be forwarded to the worker through integration into Workflow-Management-System. The failure occurrences lead to increasing gained failure knowledge. Based on this constantly growing knowledge, the decision quality concerning the failure priority and the selection of measures should be continuously increased.

The project FAMOS dealt in particular with the requirement-based input of failure information and the finding of existing knowledge within the failure knowledge database [9]. In this approach, ICT (information and communications technology) stands for the storage and use of failure knowledge within the producing company. The method assists workers in correlating suspected failure patterns to database items for which actions have previously been established. Workshops are explicitly initiated for the identified failure patterns, and measures/actions are developed to store them in the database subsequently. Thus, the approach from

FAMOS does not provide a reference process for failure management but comprises a set of IT-supported methods for creating a robust failure knowledge database.

Different from the approach from FAMOS, LINß described a reference process for failure elimination [5]. He defined seven necessary process steps, including production failure definition, failure recording, immediate action, failure analysis, corrective measures development, corrective measures implementation, and results controlling. LINß distinguished between external (cf. complaint management) and internal (cf. failure management) failure correction. His model describes the necessary tasks during failure elimination.

The approaches listed above are considered isolated failure management approaches. These isolated approaches specifically focus on the failure management processes and distinguish them from other processes in the producing company. Reference processes to be followed for successful failure elimination are mostly mentioned. We consider that providing reference process for optimized failure elimination receives special attention from many authors. What is predominantly not included in the above-mentioned approaches, however, is the consideration of the other processes in companies. Instead, the authors describe a self-sufficient design of failure management without addressing possible conflicts or intersections with other processes. In particular, little attention is paid to the interaction with the value-creating processes. Hence, the integration of failure management into the value adding production process is the focus in our work.

3. Programming of the simulation model

As described in our previous work [10], the analysis of existing failure in a production system is based on the proposed modularized analysing method according to TUERTMANN ET AL. [11]. The model observes the production system in a modularized way. Based on the modules, the construction of the failure management model in our previous work was accordingly derived. The failure management model then includes *Failure Management*, *Failure Knowledge*, *Failure Causes*, *Resources* and *Production*, extracted from the work of TUERTMANN ET AL. It is to be mentioned that in this model no individual process steps are represented, but only the manufacturing company's entire production in one calculation step. Interaction among different steps can thus not be shown.

Generally, in the model of TUERTMANN ET AL., the selected level of abstraction is too high to enable actual optimization at the level of production planning and control. In particular, the level of detail presented within the model does not allow for a simulation at the process step level, as this is necessary for calculating the key parameters to achieve better production performance. The failure management model should be enabled to map any production process in order to be able to consider specific scenarios. Hence, in our previous work [10], adjustments and further development are made to adapt the model from TUERTMANN ET AL. and make it applicable for failure management in manual assembly. A schematic structure is proposed to modularize the production steps and enable representing any number of production steps in a single model. As next step, this model needs to be programmed considering the interaction among the process steps. The corresponding parameters involved in the model need to be described in mathematical forms.

For the programming of the simulation model presented in our previous paper [10], the software *Vensim* developed by *Ventana Systems* is applied. This software was also deployed by TUERTMANN ET AL., whose model serves as the origin of the simulation model in this paper [3]. Deploying the software *Vensim* for programming the simulation model can reduce the risk of transmission failures. The programmed simulation model consists of 23 elements and is not restricted by the amount or the type of the process step. These 23 elements include ten constants, ten variables, and three additional variables with integrating behaviour. The constants are the setting parameters of the simulation model. By setting corresponding values of constants, the model can be adapted to a specific process step (PS). Table 1 provides detailed information about the constants.

Table 1: Constants of the simulation model and their description and unit

Constant	Description	Unit
Acceptable Defect Rate PS	Percentage of defective products accepted without initiating activities to correct the defect	%
Cycle Time PS	Execution time of the considered process step	Seconds/ Product
Defect Appearance Probability PS	Probability with which a present failure cause leads to an actual failure occurrence	%
Defect Registration Rate PS	Proportion of detected defects that is recorded	%
Inspection Frequency PS	Interval of product inspection	Products
Inspection Time PS	Duration of the inspection of one product	Seconds/ Product
Planning PS	Number of planned products for the process step	Products/ Day
Resource Requirement for One Defect Registration PS	Resource requirements for the recording of a defect	Seconds/ Defect
Shift Length PS	Length of a shift excluding breaks	Hours
Shifts per Day PS	Number of shifts per day	Shifts

Aside from setting parameters, variables are also involved during simulation model programming. The variables are subject to mathematical calculation rules, which must be represented in the programmed simulation model. The variables with descriptions and calculation rules can be found in Table 2.

Table 2: Variables of the simulation model and their description and calculation rule

Variable	Description	Calculation Rule
Completion Rate PS	Number of finished products related to one time unit	$\text{Completion Rate PS}=\text{Delay Fixed}(\frac{\text{Net Production Time PS}}{\text{Cycle Time PS}}*3600, \frac{\text{Cycle Time PS}}{86400}, 0)$
Conform Products Rate PS	Product flow of the compliant products	Conform Products Rate PS=Completion Rate PS*(1-Defect Rate PS)
Defect Rate PS	Percentage of defectively produced products in the process step	Defect Rate PS=Defect Appearance Probability PS*Root Causes
Defective Products Rate PS	Difference between all finished products and compliant products	Defective Products Rate PS $=\text{Delay Fixed}(\text{Defect Rate PS}*\text{Completion Rate PS}, \frac{\text{Inspection Time PS}}{86400}, 0)$
Need for Action PS	Need for action resulting from the comparison of the acceptable defect rate and the actual defect rate	Need for Action PS =IF THEN ELSE(Defect Rate PS>Acceptable Defect Rate PS,1, 0)
Net Production Time PS	Working time in hours available per day	Net Production Time PS =Required Worker PS*Shifts per Day PS*Shift Length PS -Time Spent on Inspections PS $-\frac{\text{Time Spent on Defect Registration PS}}{3600}$
Required Worker PS	Number of employees required per day and shift	Required Worker PS =Required Working Time PS/(Shift Length PS*Shifts per Day PS)

Required Working Time PS		Required Working Time PS $=\text{Planning PS}*\frac{\text{Cycle Time PS}}{3600}+\text{Time Spent on Inspections PS}$
Time Spent on Defect Registration PS	Time required for the registration of defects	Time Spent on Defect Registration PS =Defect Registration Rate PS*Defective Products Rate PS *Resource Requirement for One Defect Registration PS
Time Spent on Inspections PS	Time required for quality controls	$\text{Times Spent on Inspections}=\frac{\text{Planning PS*Inspetion Time PS}/3600}{\text{Inspection Frequency PS}}$

Different from the ten variables above, variables with integrating behaviour are primarily intended to model the material flow of the process step. The initial value of these variables equals zero. The descriptions and calculation rules of the variables with integrating behaviour are given in Table 3.

Table 3: Variables with integrating behaviour of the simulation model and their description and calculation rules

Variable	Description	Unit
Completed Products PS	Completed products of the process step	Completed Products PS =Integ(Completion Rate PS-Conform Products Rate PS-Defective Products Rate PS)
Conform Products PS	Conform products of the process step	Conform Products PS=Integ(Confrom Products Rate PS)
WIP Process Step	Work occurring in the process step	WIP Process Step=Integ(Defective Products Rate PS+Planning PS-Completion Rate PS)

In addition to the simulation model itself, the target system for performance measurement must be integrated. Only by measuring performance, the evaluation of the various failure management strategies is enabled. Performance refers to the time required for an employee to process a conform product. The overall target value of one process step is calculated as follows:

$$\text{Overall Target Value PS}=\text{IF THEN ELSE}(\text{Conform Products Rate PS}>0,\ \frac{\text{Required Working Time PS}}{\text{Conform Products Rate PS}},0) \quad (1)$$

To compare two simulation results, a further variable with integrating behaviour (Sum of OTV PS) is added. Thus, the performance achievement over the entire simulation period can be compared in only one characteristic value. The initial value is zero and the calculation rule for the variable is:

$$\text{Sum of OTV PS}=\text{Integ}(\text{Overall Target Value PS}) \quad (2)$$

3.1 Verification of the programmed simulation model

Towards the error-free programming process, tests were already carried out during model generation. It was checked after each programmed calculation rule using dimension tests whether the units used for the elements were consistent. Additionally, to check the programmed simulation model's behaviour for plausibility and to ensure that the generated links of the model elements follow logical relationships, test runs were performed. The procedure is based on the techniques of verification and validation, according to RABE ET AL. [12]. Such a test is considered a fixed or limiting value test. In this test, the simulation model is given fixed input parameters to prevent dynamic model behaviour; hence, the simulation results can be reproduced. Accordingly, fictive values were assigned to the simulation model's constants, and hypotheses were made for the resulting values of the variables. The test run confirmed all hypotheses so that a consistently alleged behaviour of the calculation rules and implemented functions are proven.

Furthermore, it was tested whether the system behaviour remains stable when the input values are changed. For this purpose, several adjustments are made to the initial model, and the expected change in system behaviour is compared with the simulation result of the adjusted model. In each case, the initial model forms the basis for the adaptation, i.e., after each adaptation, the model is reset to the initial state before the subsequent adaptation is carried out. The constants *Defect Appearance Probability PS*, *Planning PS*, and *Cycle Time PS* were respectively adjusted. The expected results after adjusting the first and second constants were confirmed. The expected result after adjusting the cycle time deviates 0.16 % from the actual result. However, the deviation decreases when the time spans between the calculation times are reduced.

3.2 Validation of the programmed simulation model using a case study

The programmed simulation model was validated using a case study from the automotive industry. The validation of the concept is carried out by comparing the simulation results with the real recorded data. Two successive assembly stations for the production of a powertrain module are considered. For each station, one employee works autonomously to carry out all the tasks required at the station. If several workers are involved, they perform the same activities in parallel on the same type of product. In the following, the work

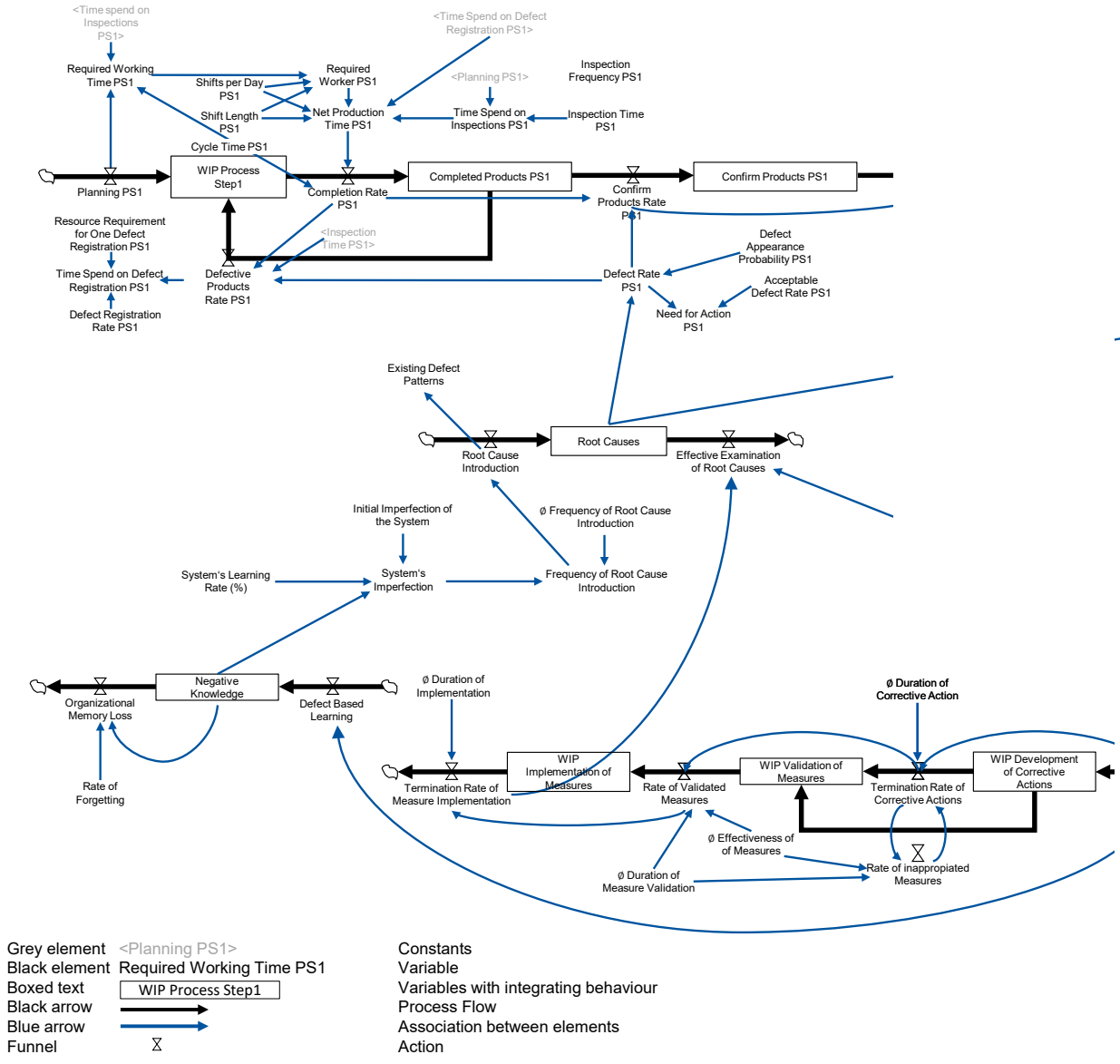

Figure 1: First part of the overall model of the use case

stations are referred to as Station 1 and Station 2 according to the sequence in which they are to be performed. A total of eleven different tasks are performed at Station 1 and eight at Station 2.

To begin the simulation model must be adapted to the case study. Since two process steps are considered, two model modules must be connected in series. It is necessary to link these models with the sub-models Failure Management, Failure Causes, and Resources. These sub-models can be taken over to a large extent from the approaches according to TUERTMANN ET AL. [3]. An adaptation of the sub-models must be carried out primarily regarding the respective interfaces. The need for action in failure management is determined based on the need for action in the individual process steps and can no longer follow directly from a model of the entire production process. In Figure 1 and **Error! Reference source not found.**, the overall model of the use case is visualized.

As a sequent step, the failure occurrence probability of stations 1 and 2 must be determined. The probability is determined according to the Expert System for Task Taxonomy (ESAT) [13]. The prerequisite is the

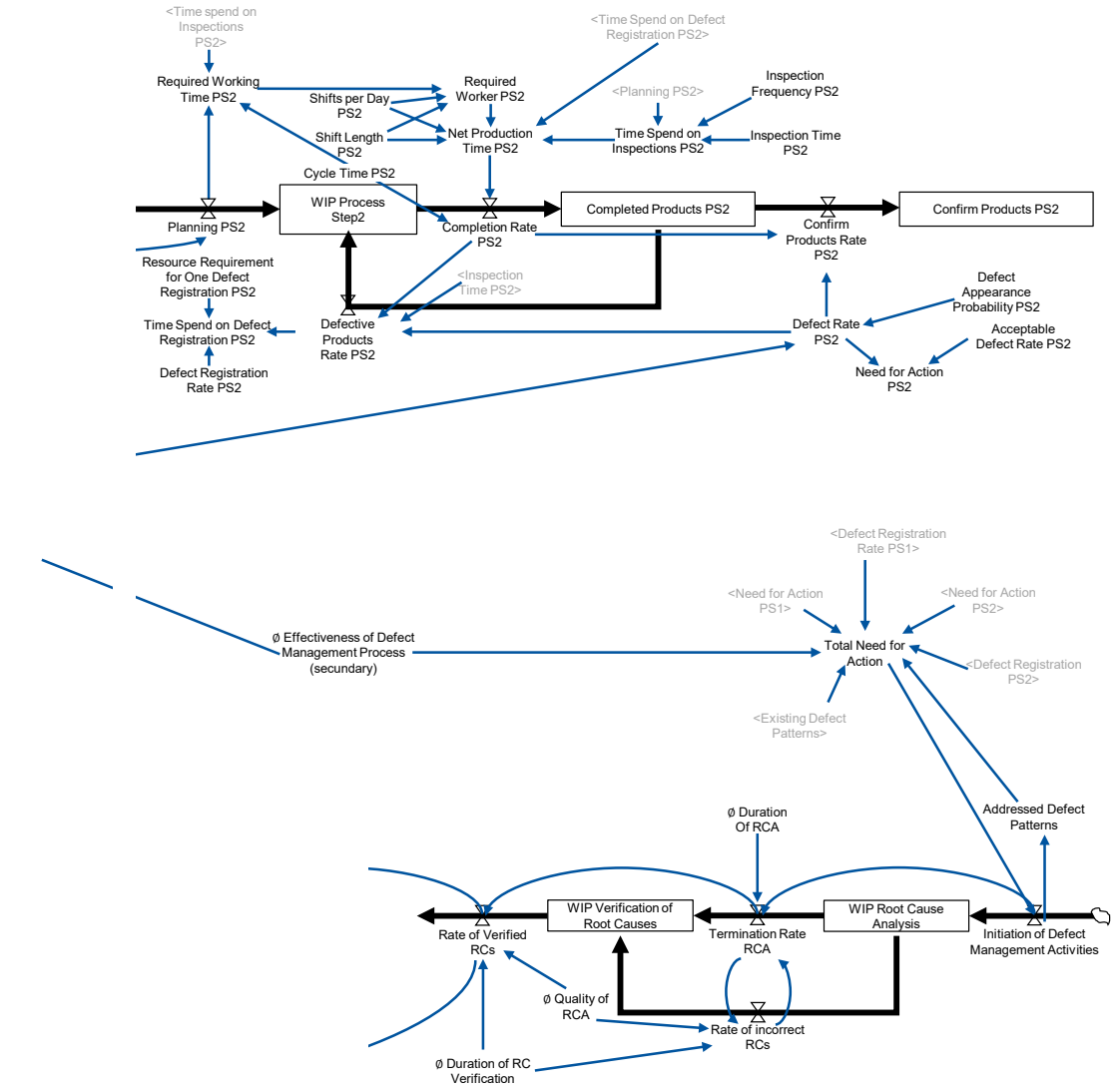

Figure 2: Second part of the overall model of the use case

description of the tasks at stations 1 and 2. A corresponding task catalogue was created in a workshop with the foremen and workers of the assembly line.

Once all other input data, such as cycle time, has been collected for both stations, the simulation model can be executed. In order to calculate the actual failure rates, all units produced in 2016 were considered. In total, 100,000 units were produced at the respective stations during this period. To determine the failure rate, all failures that occurred during this period were considered, and those failure types were selected that could be traced back to a failure at assembly stations 1 or 2. At station 1, the simulation result is 12 % below the actual value, and at assembly station 2 is 1 % above. Assuming that the standard deviation of the absolute number of failures is in each case only one failure (related to one year), a tolerance range in terms of process dispersion can be defined to +/- 3 sigma (station 1: +/- 20%; station 2: +/- 2%). The deviations of the simulation result from the actual value are within this 3-sigma range and are therefore considered as an acceptable deviation. In conclusion, the programmed model is valid [11].

4. Derivation of general recommendations for action for failure handling using a case study

Subsequently, the verified and validated model was used to generate recommendations for the optimal integration of failure management into the production process. For this purpose, another case study was considered, which has a significantly lower process level than the validation case study. This case study also comprises two process steps of a manual assembly line. Simulations were performed over 50 days. In these simulations, the failure management strategy was continuously varied. A failure management strategy is defined as setting values for the constants *Acceptable Defect Rate PS* and *Defect Registration Rate PS*. Accordingly, a variation of the strategy is equivalent to a variation of the input values of these two constants. In order to determine the performance over the entire simulation period, the variable *Sum of OTV PS* was evaluated by relating the result of one run to the result of the baseline situation.

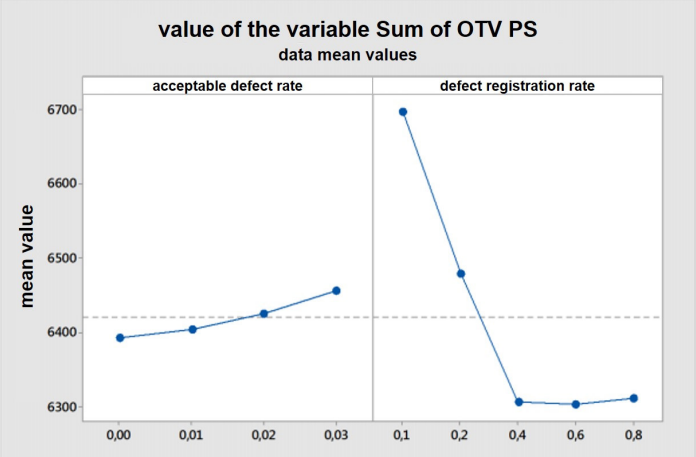

Figure 3: Influence of the failure management strategy on the performance

The best results were obtained for a minimum acceptable defect rate and a defect registration rate around 50%. In addition to the overall strategy's performance, it was also possible to analyse the influences of the acceptable defect rate and defect registration rate on the performance. For this purpose, the defect registration rate was varied at a constant acceptable defect rate. Only after 15 days of simulation and variation, respectively increase of the defect registration rate, an improvement of the performance became visible by the value of the variable *Sum of OTV PS.* From a defect registration rate of approximately 40 % onwards, no further improvement could be identified. According to the simulation results, it is therefore not expedient to capture all failures since after a limit value has been exceeded, no further improvement in performance can be achieved. That indicates that there is an optimal defect registration rate that must be set to maximize performance.

As following step, the acceptable defect rate was varied at a constant defect registration rate. The simulation results show that the influence on the acceptable defect rate's performance is significantly lower than the one of the defect registration rate. The variable *Sum of OTV PS* has its highest value on day 15, and with lowering the rate, the value drops again. To further characterize the influence of the acceptable defect rate and a defect registration rate, variance analysis was performed. For this purpose, the variable *Sum of OTV PS* was defined as the target variable and the two constants are set as factors. In Figure 3, the variance analysis results to characterize the influence of the failure management strategy on the performance are illustrated.

5. Conclusion

Based on the simulation results, it was shown that by adjusting the failure management strategy, the time required for an employee to assemble a compliant product could be reduced. For this adjustment, the defect registration rate and acceptable defect rate are the levers. It was also found that an optimum for the defect registration rate exists. The defect capture rate describes the proportion of existing product defects fed into a failure management process to eliminate the cause of the failure. A defect registration rate below the optimum can lead to a significant drop in performance in the entire production system. Maximization of the defect registration rate towards 100 % causes inefficiency since the resulting additional effort for defect detection can no longer be compensated by the increased performance of failure management.

The results show that a System Dynamics model can be used to derive recommendations for optimizing failure management. This allows measures to be identified for better interconnection of a company's failure management strategy with its production planning and control, taking into account the mutual interactions. However, the efforts of the remaining personnel in failure management are not included in the optimization. There is potential for expansion in terms of integrating a role model so that the efforts of the failure management in the different groups of persons can be included.

The simulation model is based on a static strategy, which means that the defect registration rate and acceptable defect rate are defined initially and are not further adjusted afterward. Especially concerning the consideration of a production ramp-up, an adjustment of the failure management strategy depending on the time seems to be reasonable. The integration of a dynamic strategy is a potential extension possibility of the model to increase the model quality.

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Biography

Junjie Liang (*1995) studied industrial engineering at RWTH Aachen University. Since 2020, he has been working on his doctorate as a research assistant at the Laboratory for Machine Tools and Production Engineering of RWTH Aachen University, focusing on production optimization and production data modelling.

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