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Analysis of the behaviour of flexibility parameters in intralogistics systems

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Abstract

Today's logistics systems are characterized by uncertainty and constantly changing requirements. Rising demand for customized products, short product life cycles and a large number of variants increases the complexity of these systems enormously. In particular, intralogistics material flow systems must be able to adapt to changing conditions at short notice, with little effort and at low cost. To fulfil these requirements, the material flow system needs to be flexible in three important parameters, namely layout, throughput and product. While the scope of the flexibility parameters is described in literature, the respective effects on an intralogistics material flow system and the influencing factors are mostly unknown. This paper describes how flexibility parameters of an intralogistics system can be determined using a multi-method simulation. The study was conducted in the learning factory "Werk150" on the campus of Reutlingen University with its different means of transport and processes and validated in terms of practical experiments.

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1. Introduction

Uncertainty and constant changes affect both production and logistics. Increasing demands for customised products, short product lifecycles, and a large number of variants are just several examples of these challenges [1,2]. These outlined aspects are the cause of increasingly complex dynamics in logistic flows, which ultimately require long-term changes to the network structure in addition to short-term adjustments to network capacity [2]. To be successful as a company, change must be continuously shaped and controlled [3]. Key concepts in this context are flexibility and versatility [4,5]. While flexibility describes the ability of a system to adapt to changes within a defined area or flexibility corridor, versatility refers to a system's ability to make rapid and sustainable structural changes [6]. In particular, intralogistics transport systems must be able to adapt to changing conditions at short notice, with little effort and at low cost [7]. This is due to the fact that material flows link production systems and must therefore meet their requirements.

The main requirement for material flow systems is adaptivity to changes in structure, quantity, and product. However, material flow systems often fail to meet this requirement because adaptation to the production system is usually accompanied by a high level of modification expenses [3]. In order to plan a future-oriented intralogistics material flow system, a certain degree of flexibility with regard to these factors is required. In the literature, these factors are referred to as layout flexibility, throughput flexibility, and product flexibility [8]. The behaviour of these flexibility parameters, however, are unknown, which limits productivity and prevents a precise planning.

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To quantify these three parameters, influencing factors based on literature were defined for each. In a subsequent step, a simulation model of the learning factory Werk150 of the ESB Business School at the campus of Reutlingen University was developed. To ensure that the simulation model correctly reflects reality, numerous verification and validation methods were applied, including practical experiments. Ultimately, the impact of the individual influencing factors regarding the intralogistics material flow systems throughput, output, and degree of utilization of the used means of transport was simulated.

2. Flexibility parameters in intralogistics material flow systems

In literature, several flexibility parameters can be found, all of them having a different definition in terms of their scopes and names [3,9-11]. According to a study by Heinecker [12] regarding flexibility parameters in intralogistics material flow systems, there are three independent parameters in total: layout flexibility, throughput flexibility, and product flexibility. All other parameters are either used synonymously or can be formed by combining these three parameters [12].

For the analysis of the behaviour of these flexibility parameters in intralogistics material flow systems, influencing factors need to be defined. A summary of the definitions used and defined influencing factors of the flexibility parameters can be found in Table 1.

Table 1. Definition of flexibility dimensions in intralogistics and their influencing factors.

Parameters	Definition	Influencing Factors
Layout Flexibility	A layout-flexible material flow system can use any route in the system to transport goods from different sources to different sinks to keep the corresponding machines operating as required.	Reachability of sources and sinks, Material flow route length
Throughput Flexibility	A throughput-flexible material flow system can cope with fluctuations in throughput.	Means of transport speed, Means of transport capacity
Product Flexibility	A product-flexible material flow system can transport a range of products and variants without setup processes; the products can, furthermore, differ in terms of their dimensions and weight.	Product dimensions, Product weight

3. Development of the simulation model and results

As the analysis of the behaviour of these parameters is highly complex, due to the existing interdependencies, a static calculation of the behaviour of all parameters is not possible. Thus, a simulation model was developed according to the process model of Gutenschwager et al. [13]. In the following, the simulation framework, simulation model structure and the simulation results of the Werk150 are presented.

3.1. Simulation framework of the Werk150

For the analysis of the behaviour of the flexibility parameters, the intralogistics system of Werk150 was used as research and validation environment. The learning factory Werk150 at ESB Business School (Reutlingen University) represents a realistic production and logistics environment and was founded in 2014 [14]. The available infrastructure of Werk150 allows the realization of changeable production scenarios to store, assemble, pack, and ship multivariant city scooters [15].

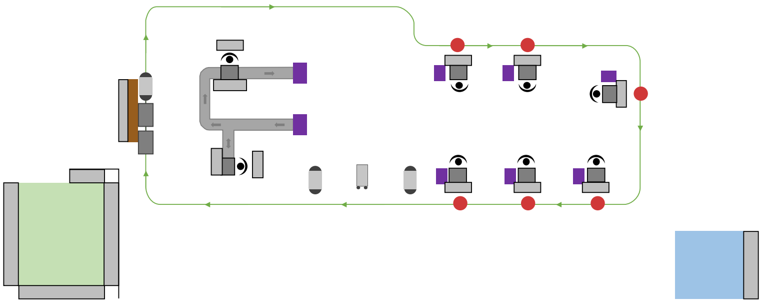

Fig. 1. Layout of the production system of the Werk150.

As can be seen in Fig. 1, the investigated production system consists of a goods receipt area (green area), a supermarket warehouse (brown area), two order-picking stations that are connected with a conveyer belt, six workstations, and a goods issue (blue area). While in the goods receipt all A-parts required to produce a city scooter are stored, the supermarket contains all C-parts. C-parts are those with a low-value share and a high-quantity share, while A-parts are those with a high-value share and a low-quantity share. In order to produce a city scooter, the incoming customer order is divided into two modules: stem and base. Whilst the first order-picking station picks the items for the stem, the second station picks the items for the base. In both cases, all required A-parts are placed in a product fixture. After completion of the picking, the product fixtures for the base and stem gets transported to four subsequent workstations, which are selected depending on their occupancy. At these workstations, the respective modules are assembled using the corresponding C-parts. Once the modules are completed, the product fixtures are transported to either of the last two workstations. Here, the final assembly of the city scooter takes place, where both modules are merged together. Finally, the scooter is getting packed and transported to the goods issue. The two product fixtures are transported back to the order-picking stations.

For the transport of the components, the system uses four different means of transport. The city scooters, product fixtures and A-parts are transported by either an automated guided vehicle (AGV), a mobile collaborative manipulator (AGV with Kuka Iiwa robot), or a human. The small load carriers (SLC) for the C-parts are transported using a collaborative tugger train, developed within the research project “Collaborative Tugger Train 4.0 (KollRo 4.0)”. While the AGV, mobile Kuka Iiwa and the human can navigate freely on various dynamic routes within the production environment, the KollRo with its trailers is considered to only operate on a predefined route in one direction to simplify traffic planning and collision avoidance.

The assumptions made during the development of the simulation model idealise the real intralogistics system of the Werk150 and, for example, ignore minor aspects. Thus, only one product with two variants was considered. The production sequence for the city scooters cannot be changed and no set-up processes are required. Machine breakdowns, external supply bottlenecks, working hours of employees, or other factors affecting production were not considered. Furthermore, it was assumed that the system produces at maximum capacity. Thus, the measured system throughput reflects the maximum possible production output. With regard to the means of transport, the speed, acceleration, curve radius, type of navigation, load carrier capacity, total cargo load, and the parameters are considered, next to loading and unloading times. Factors, such as machine failures, battery charge status, motivation or stress of humans were not considered.

3.2. Structure of the simulation model

The simulation model for analysing the behaviour of the flexibility parameters was developed using a multi-method simulation software. Depending on the level of detail required, either a discrete event modelling approach or an agent-based modelling approach was used. Main element of the simulation model is the production system and the generation of the customer orders, where each order has the same probability of either being the city scooter variant Flex Blue or Flex Air. Directly after generation, the customer order is divided into two work orders for the stem and base. The first step of the work order is the picking of A-parts onto the respective product fixture at the two order picking stations. After picking, both stations request a transport to transfer the fixtures to one of the subsequent workstations. The selection of the workstation is based on their respective occupancy. Once the assembly of the stem and the base with C-parts has been completed, another transport request is placed, which transfers the two product fixtures to one of the two available final assembly stations. There, the stem and base are bolted together and the city scooter gets packed. Ultimately, a transport request is reported, which transports the finished city scooter to goods issue and deliver the two empty product fixtures back to the order picking stations.

Next to requesting a transport for the product fixtures, every workstation can also place a material request for A- or C-parts. All requests are consolidated in a database, which is continuously queried in a cyclical event in order to generate a transport order. If there are any entries in the database, the event is not terminated and the selection of a suitable and available means of transport takes place. For the selection, all transport restrictions relevant to the means of transport are taken into account, such as the maximum transporter capacity or the small load carrier (SLC) dimensions. If no suitable vehicle is available, the process is terminated. In case the first request is a material order, and several means of transport are available for processing, the means of transport with the highest filling level is selected. Should there be more than one material order in the database, the existing transport order is extended by the "getAdditionalOrders" process, under consideration of the means of transport restrictions. In case the first request is a product fixture, the process is directly terminated and a transport order is generated, due to the transport restriction that only one product fixture can be transported per means of transport. Fig. 2 summarises the described process flows of the simulation model for the production system and the transport order generation.

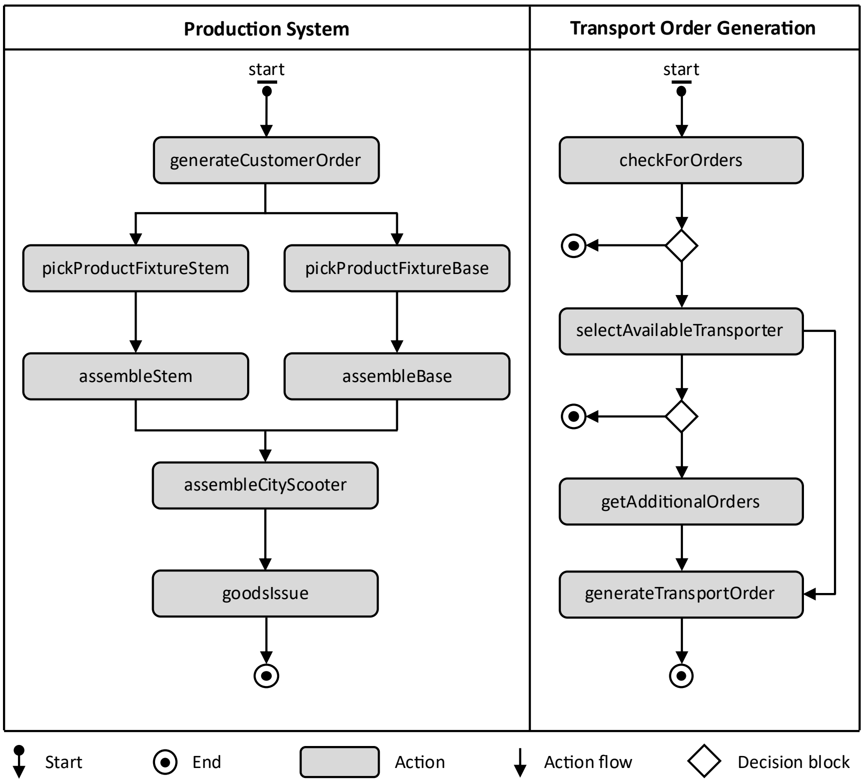

Fig. 2. Flow chart of the simulated production system and the transport order generation process.

In order to ensure that the developed simulation model adequately reflects the production system of the learning factory Werk150, a total of seven verification and validation techniques according to Gutenschwager et al. [13] were applied. Besides the animation and trace analysis technique, extreme condition tests as well as submodel testing were used for verification. In terms of validation, a face validation was carried out throughout the entire development process of the simulation model. Here, various research associates from different departments of the Werk150 were able to question and check results as well as development stages for consistency. In addition, an internal validity test was carried out to check for inconsistent fluctuations in simulation results. Ultimately, practical experiments in form of an event validity test were conducted, to demonstrate that the general behaviour of changing the individual influencing factors in the simulation model corresponded to that from the real system.

3.3. Simulation results

In the following, the simulation results are described with respect to the throughput, output, and degree of utilisation of the system elements, as these figures are one of the most important ones in material flow planning according to Noche and Druyen [16]. For each conducted simulation experiment, the starting filling levels of the SLCs as well as the degree of assembly per city scooter were randomised. This ensured that the results were not influenced by the initial ramp-up behaviour of the system. With regards to the influencing factors, only one factor was manipulated as a percentage of its initial value and set to a specific level during each experiment. Thus, the isolated effect of the respective factor on the system is obtained. In total 20 simulation runs per factor settings with a duration of one hour were carried out, from which the mean values can be calculated to obtain a single data point on the throughput, output, and degree of utilisation curve. This process is repeated for each influencing factor until its curve shows either an asymptotic behaviour or a logical limit is reached, for example, when the product weight has risen over the maximum possible transporter capacity and thus the production output is zero.

The first factor to be analysed in the scope of layout flexibility was the reachability of sources and sinks by the considered means of transport. Thereby, the means of transport individual scope of reachable sources and sinks was changed throughout the simulation experiment. In the conducted experiment, the system was simulated with two factor settings. The first setting was the initial and unchanged system, while the second setting simulated 100% reachability of all sources and sinks of all considered means of transport. Thus, a completely layout-flexible system was simulated. With the initial system settings, an average throughput of 185 SLCs per hour, with a production output of 15 city scooters per hour and a degree of utilisation of the transport system of 45% was established. In comparison to the fully reachable system, a 20% increase in throughput was achieved, with a production output of

18 city scooters and a degree of utilisation of 47%. This overall increase in performance is attributable to better utilisation of the means of transport in terms of availability and fill levels per transport. As a logical consequence of increased throughput in this system, production output has also increased.

The second factor analysed in the scope of layout flexibility was the material flow route length. By manipulating the distances between sources and sinks in percent, the factor indicates especially in the planning phase of a logistics system if transport routes need to be shortened and whether layout changes to the workstations may be necessary. With regards to the simulation experiment, the material flow route length was analysed in range from 1-800% in steps of 25%. Both parameters for throughput and output converge towards 0 as the material flow routes become longer. With regards to the degree of utilisation, the transport system converges towards its maximum utilisation. In contrast, for very short material flow routes, the breakeven performance of the production system establishes, which is 200 SLCs per hour for throughput and 16 city scooters for output. The degree of utilisation is at 40%, where the transport system is approaching both its kinematic limits (i.e. the acceleration and deceleration of the means of transport) and those of the production system. Thus, the degree of utilisation achieved corresponds to the system-inherent base utilisation to comply with the existing production process.

The second flexibility parameter analysed was the throughput flexibility, which is influenced by the means of transport speed and capacity. To analyse the influence of the means of transport speed on throughput, output and degree of utilisation in a simulation experiment, the speed of all vehicles was changed as a percentage of their initial values in the range of 1-200% in steps of 10%. As a result, the throughput and output of the system showed a degressive trend. Whereas both parameters have a stronger increase by changes at lower speeds, a plateau for higher speeds establishes. With regards to the degree of utilisation, a regressive trend was observed. While there was a high utilisation rate for lower speeds, a plateau emerged for higher speeds. All three plateaus for throughput, output and degree of utilisation correspond in terms of their values exactly to the breakeven performance of the system, which was also obtained during the simulation experiment for very short material flow routes.

To simulate the effects of the means of transport capacity, the number of possible SLCs to be transported per vehicle was also changed as a percentage of their initial values in the range of 1-200%. The step size between each experiment was 25%, as no smaller steps were logically necessary due to the individual transport capacity. As the resulting means of transport capacity is not always an integer, the resulting behaviour is discontinuous. In general, the simulation results provide information on whether the current system can cover future requirements with its capacities or not. If this is not the case, complementing simulation experiments can be conducted with different means of transport, to determine which vehicles need to be upgraded, replaced, or supplemented. Regarding the impact of the means of transport capacity on the system, a trend was observed where higher capacities lead to higher throughput and output, while lower capacities lead to a complete production stop as essential parts can’t be transported anymore. With respect to the degree of utilisation, a very system-specific behaviour establishes as in certain simulated capacity ranges the means of transport can’t operate due to transport restrictions. This resulted in a degressive trend whose maximum utilisation establishes at the initial capacity of 100% of the system.

The last flexibility parameter analysed was the product flexibility, which is influenced by the product weight and dimensions. As the influence of the product weight can be statically determined by comparing the heaviest object to be transported on each material flow route with the maximum load capacity of the respective operating means of transport, a simulation was not required. The maximum product weight was 10kg. With respect to the product dimensions, any load carrier size can be simulated. In the conducted simulation experiment, only the three standard SLCs according to VDA 4500 and DIN EN 13199-1 were considered. Similar to the experiment of reachability, two states were simulated of which the first state represented the initial system with the SLC4030 for A-parts and SLC2030 for C-parts. The second state considered the next bigger SLC6040 and SLC4030 respectively. As a result, the throughput and degree of utilisation was reduced by 20% while maintaining the same production output. This effect is attributable to the fact, that the number of components per SLC increased with the load carrier’s dimension.

4. Practical application of the simulation results

With the knowledge gained about the individual behaviour and effects of the flexibility parameters on the intralogistics system, better strategic planning regarding the activation of flexibility potentials can take place to avoid expensive and unused flexibility capacities. Thereby, sales programs with current as well as future demanded product quantities are combined with the simulation results to determine the maximum operating time of the current intralogistics material flow system without technical adjustments (see Fig. 3). Based on this period, provisions can be build-up at an early stage, which in turn can be used for the required system expansion.

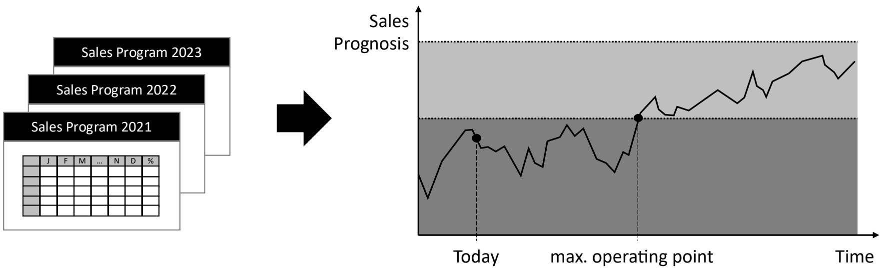

Fig. 3. Sales forecast with the maximum operating point of the intralogistics system.

Furthermore, the simulation results can be used in combination with the sales programmes to efficiently plan the required system capacities in the future. Thereby, the required capacities are first determined. Subsequently, the individual parameter behaviours can be used to check which measures (e.g. increasing reachability or the means of transport speed) are the most effective ones in terms of achieving the required capacities in the future. Based on these possible options, an evaluation regarding the economic efficiency for each measure can be conducted. Ultimately, the most effective and economically efficient option is selected and planned in more detail.

5. Summary

As described above, the simulation results of the individual flexibility parameters are very system-specific. However, by simulating the individual influencing factors of the respective parameters, a variety of statements can be made with regard to the current system and variations of it. For instance, by simulating different degrees of reachability, not only can the limit of layout flexibility of the current system be determined, but also different layout-flexible means of transport can be simulated. Furthermore, statements regarding the theoretical maximum utilisation of the used transport system can be made, by eliminating all process times in the production process.

With regards to learning factories and with the help of such simulation experiments, interested participants can be taught the basics of simulation on the one hand as well as the planning of flexible material flow systems on the other hand. In the form of case studies, various complex market requirements can be presented to the participants and their simulation models and material flow systems, which they have to meet through activation of certain flexibility potentials in a targeted manner. In this way, the participants learn interactively which levers they can use to make their systems more flexible and what impact their decisions have on the throughput, output and degree of utilisation of their means of transport.

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