Physics Simulation of Material Flows: Effects on the Performance of a Production System

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Abstract

In cyber-physical production systems, material flows show complexity due to varying physical aspects of transported work pieces and autonomously selected transport routes. As a result, physically induced disturbances that may lead to delays or damages are hard to predict. The on-line usage of a physics engine offers potential to derive material flow parameters that enable safe transports with optimized accelerations. Previous work showed the feasibility of this approach and potential operational benefits through faster material flows. In consequence, the scope of this paper is to apply discrete-event simulation to investigate whether physics simulation of material flows leads to positive impacts on production system performance indicators such as throughput times and capacity utilization. The results indicate that increased velocity and acceleration of material flows can positively influence these indicators. In consequence, applying physics simulation to ensure safe transports with such high velocities and accelerations can improve the overall performance of a production system.

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1 Introduction

Modern production is largely influenced by cyber-physical systems (CPS), which contain embedded systems that interact with real processes through sensors and actuators. In addition, CPS interact both with the physical and the digital world and are connected with each other and in global networks [6]. The application of CPS within manufacturing leads to the term of Cyber-physical production systems (CPPS). In CPPS, CPS in the form of e.g. machines or material handling systems are linked within and across all levels of production, CPPS are a key feature of Industry 4.0 and enable flexible and adaptive manufacturing of customized products in small lot sizes [27]. The individual character of products is reflected in individual work plans and process sequences that are required for their production. In consequence, also the routes that individual products take through a CPPS as part of the material flow often vary. On these different routes, the physical behavior of the workpieces

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during material handling might vary due to different aspects of the factory layout (e.g. ramps or curves). This complexity in the material flow, which is defined as the movement of discrete objects on transport ways or conveyors in steady and unsteady time intervals [3] is increased by product variations. As a result of customization, products can differ in terms of physical characteristics such as mass, inertia or surface roughness. Such differences increase the risk of physically induced disturbances that affect safety of employees or equipment as well as the operation of the production system. These disturbances (e.g. a workpiece that tips on a conveyor) are a result of the physical interaction between workpieces and material handling systems. In order to anticipate the described disturbances, material flows in industry are commonly performed at rather low velocities and accelerations. In this manner, the exposure of handled products and workpieces to dynamic influences (as described above) is minimized, since slow velocities and accelerations lead to small inertial forces during the material flows. In consequence, material flows take a relatively long time and potential for faster material flows often remains unexploited. Physics simulation is able to evaluate individual material flow constellations and to subsequently determine fast but safe material handling parameters such as velocity or acceleration. This approach bears potential to increase the velocity of different material flow processes individually, potentially resulting in reduced lead times and therefore an improved performance of the overall production system. In order to investigate this effect, the goal of this paper is to describe the fusion of a physics simulation model that can calculate optimal parameters on the material flow level with a discrete-event simulation model that simulates the operation of the entire production system. Based on this coupling, the effects of different velocity and acceleration configurations in a production system are quantified.

2 State of the art

2.1 CPPS

Advances in information and communication technologies have fostered the increasing implementation of CPS in several industries. Within a CPS, embedded systems, which monitor and control real physical processes by means of sensors and actuators, are connected to the global digital networks via communication facilities [6]. The embedded systems monitor and control real physical processes by means of sensors and actuators. If several CPS are networked within production, they form a CPPS. The networked elements of a CPPS consequently acquire information from their environment and act autonomously. A CPPS is thus able to react to internal and external changes [27]. Within the framework of the cooperative characteristics of a CPPS, elements such as machines, transport systems or operating resources exchange information independently. This results in adaptive, self-configuring and partially self-organizing production systems. CPPS can be seen as a measure of manufacturing companies to cost-effectively produce customized products that are increasingly demanded by customers. A key component of CPPS is the diversion from traditional, centralized control architectures. Traditionally, operations on the factory level were performed based on centralized planning. Since CPS allow connections as well as computation and on-demand control of actuators, even high-level decisions can be directed to individual entities on the shop floor level without further efforts. This enables decentralized control as well as high flexibility. Individual resources can communicate their current status and production tasks can be allocated to other resources instantly. Decentralized processing can be utilized in order to perform short-term scheduling [27]. One common control approach for of CPPS is agent-based control. In this method, each CPS-based manufacturing resource comprises a software agent that communicates with the respective agents of other resources and work pieces in order to control production processes. Using these decentralized control approaches, manufacturing tasks can be assigned to production resources dynamically, which creates individual production sequences [40]. Often, redundant machines negotiate with products and among each other in order to self-organize the manufacturing sequences of varying products [41]. In consequence, each product can take different routes through the CPPS. This is depicted in Figure 1 by showing the routes of example material flows through a CPPS. Material flow complexity can result from the number of workstations that are passed for one product, as well as from the variance of paths: The routes that workpieces and products take are not known before the actual execution due to short-term routing and redundant workstations. On these varying routes, different physical influences such as curves or ramps might occur. As a result, even the identical product variants might show different material flow routes and different physical influences. In this context, CPPS show similarities and

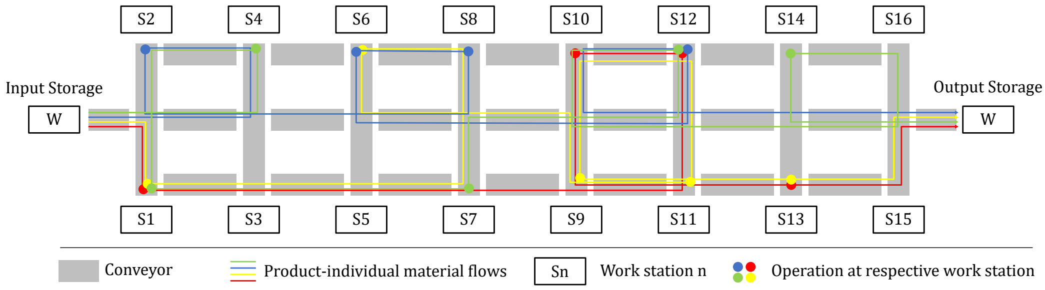

Figure 1 Varying routes in CPPS [19].

utilize common principles as flexible manufacturing systems (FMS) or matrix manufacturing systems (MMS). FMS comprise universal workstations (e.g. machine tools or assembly machines) and material handling systems to enable the flexible production of mid-volume and mid-variety production. FMS are capable of processing a variety of different part variants belonging to the same family simultaneously at the various workstations, and the mix of part styles and quantities of production can be adjusted in response to changing demand patterns [11]. Similarly, MMS are composed of modular workstations that are connected by a flexible transportation system. Through redundant workstations, the individual routing of the material is not known beforehand [13]. Both concepts provide flexibility regarding the manufactured products based on their architecture and composition. CPPS add to this flexibility by enabling decentralized control through the enabled communication between machines. Therefore, CPPS are often structured according to the principles of MMS or FMS, which is also the case in this study. Summarizing, CPPS are suitable for the economic production of small lot sizes that are a result of customization. Amongst other aspects, this flexibility is achieved through agent-based, decentralized control. These two characteristics impose challenges on the physical material flows, which are elaborated in the next subsection.

2.2 Material flows in CPPS

As described, meeting customer demands for individual products is one of the key requirements that today's production systems and thus CPPS need to fulfil. Product variety leads to a wide span width of product variants, in basic models as well as in variants within the models [43]. Depending on the extent of customization, objects (both finished products or workpieces) that are handled within material flows may have varying physical attributes like shape, size, mass, inertia or surface roughness [8]. In consequence, the interaction between these objects and material handling systems may vary as well. Furthermore, even identical products may pass through CPPS on different routes where they can experience varying physical influences due to characteristics of the factory layout (e.g. inclinations or curves) [16]. As a result of these influences, the physical behavior of each material flow process in CPPS may become highly individual. The physical behavior of processes in material handling systems that can lead to the described disturbances is determined by certain operating parameters (e.g. the acceleration or the torque of the actuators). These parameters however often not only influence the physical behavior, but also affect the performance of the material handling system and therefore the overall production system. For instance, if a material handling system is operated with higher velocities and accelerations, this will lead to the positive effect in terms of faster material flows and shorter throughput times [22]. However, as a tradeoff, this measure also imposes higher inertial forces on the transported workpieces, which increases the chance of disturbances as described earlier. The goal of reduced disturbances while achieving high transport accelerations and velocities could be accomplished by fixtures for load securing. However, in case of customized products, these mechanisms need to provide a high degree of adaptability which leads to high cost and complexity. Furthermore, load fixing increases the material handling time and therefore throughput time, especially if a high number of transport processes is required. Another frequently used solution is to perform material flows with slow velocities and accelerations to exclude the possibility of disturbances. As a result, most transports in today's industrial material handling systems are performed slower than necessary, which leads to the longer transport durations. A promising approach to overcome these disadvantages, is to automatically select operating parameters of material handling systems according to type and characteristics of the transported load [2]. This requires special simulation techniques that would involve physical modeling. Discrete-event simulations that are commonly used to simulate material flows on the production system level do not allow to find physically suitable parameters. Instead, a possible approach to maximize the performance of the material handling system while preventing disturbances is the usage of physics simulation to simulate the physical interaction between workpieces and material handling systems during every individual material handling process. Performing physical simulation requires a deeper understanding of the mechanics that is of relevance during material flows. As described in [18], material flows are mostly performed with horizontal movements. This is the case in many common material handling systems like automated guided vehicles (AGVs) or conveyors. The physical behavior of an object that is carried on such a material handling system can be described as a mechanical system as depicted in Figure 2. Frequently, carried objects are held in place by a frictional contact between the objects surface and the material handling systems load bed. This common application scenario is shown in the figure. This requires a deeper understanding of the mechanics that is of relevance during material flows. As described in [16], material flows are mostly performed with horizontal movements. This is the case in many common material handling systems like automated guided vehicles (AGVs) or conveyors. Frequently, carried objects are held in place by a frictional contact between the objects surface and the material handling systems load bed. The physical behavior of a carried object in this common application scenario is shown in the simplified mechanical system in Figure 2: The object, indicated by a grey box has a mass that leads to a resulting gravitational force F_g. External forces F_{ext} and Moments M_{ext} of varying cause can apply. All dynamic influences lead to a resulting Force F_{res} and a resulting Moment M_{res} that act on the center of mass of the regarded object and define the physical behavior of this object.

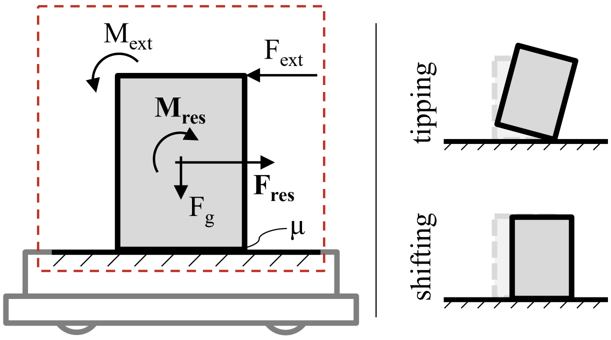

Figure 2 Mechanical system of material handling (after [18]).

Regarding horizontal material flows, disturbances occur, when the transported work piece is dislocated from the material handling system, which induces e.g. shifting or tipping. This applies, when the magnitude of F_{res} and M_{res} outweigh frictional and gravitational forces that hold the object in place. The occurrence and the extent of such disturbances are a result of the constellation of the following influencing factors:

- **Mass distribution of the workpiece:** The inertia of the work piece as well as the location of its center of mass. This is often a result of the aspect ratio of the work piece. In general, tall work pieces with a large height-to-width (in movement direction) ratio tend to tip, while flat workpieces are more likely to shift.
- **Friction between the workpiece and the material handling system:** The higher the friction coefficient µ between the workpiece surface and the material handling system at the respective contact surface, the less likely is the workpiece to shift.
- **Accelerations:** According to Newton's second law of motion, accelerations of the material handling system cause a force which applies at the center of gravity of the workpiece. This may result in tipping or shifting.
- **External forces and moments:** Furthermore, the application of external forces and moments may cause disturbances as well (e.g. collision with factory infrastructure).

Based on these fundamental mechanical correlations, several disturbances in industrial practice may occur: Workpieces can fall off a conveyor or tip over because of acceleration forces [44]. Workpieces that have fallen or otherwise changed their orientation on a conveyor can induce jamming of the material handling system and result in downtimes [20]. Therefore, material handling systems in industry need to be stopped smoothly to prevent the tipping of transported objects. This removes the necessity for additional load securing [36]. Material handling systems when considering the above problems are often operated at rather low velocities. For instance, automated guided vehicles (AGV) usually move with velocities in the range of 1 m/s, which is slower than a walking adult. Also, stationary conveyors like transfer systems operate at comparably low velocities in the range of 0.2-0.3 m/s [10, 5]. An advantage of these slow velocities is that they minimize the dynamic influences on the transported workpieces. Slow transport mostly involves slow accelerations, which in turn reduces the inertial forces that act on the workpieces during accelerating and stopping. Also, centrifugal forces in curves are mostly noncritical in these velocity ranges. In consequence, the risk of physical material handling disturbances is comparably low. However, material handling is estimated to cause about 40-80% of all operating cost within a production system [37]. It is considered as a non-value adding element during the manufacturing of a product. Non-stationary material handling systems are subject to the described disturbances as well.

Automated guided vehicles (AGVs) enable flexible routing and are therefore frequently used in manufacturing. Maintaining load stability is crucial for AGVs, because loads can tip in narrow curves due to centrifugal forces or during emergency stop situations as a result of the load's inertia [34]. Especially in environments that are shared with employees, AGVs must have the ability to stop within a safe distance, which usually defines the maximum AGV velocity [23]. Therefore, AGV velocity is mostly limited to values around 1 m/s to generally minimize the risk of loads falling off due to inertia or centrifugal forces [24]. Besides AGVs, loads falling off fork lifts are responsible for a majority of fatal injuries in industrial environments, often resulting from operators misjudging the varying physical attributes of the transported load in combination with the dynamic behavior of the vehicle [38]. As these examples show, physical attributes of loads can cause disturbances resulting from the interaction with different material handling systems, often resulting from horizontal accelerations. The result can be accidents, damage to products or to factory infrastructure, increased downtime of material handling systems, longer delivery times and additional cost. Considering the fact that material handling accounts for about 50% of all industrial injuries [37] and constitutes 15% to 70% of the manufacturing cost of a product [12], preventing the described disturbances bears potential to increase safety and economic efficiency of a production system. Summarizing, disturbances that result from the physical interaction of material handling system operation and the transported workpiece can lead to damages and delays up to injuries of staff and are therefore to be prevented. Previously, most material flow systems used to handle a limited number of products and workpieces. In consequence, if a certain configuration led to disturbance-free operation of the material handling systems, this configuration could be applied for all upcoming material flows with the same workpieces and routes. This is often a result of trial and error. However, as stated above, both product and flow variance can make every material flow unique and unprecedented in CPPS. Thus, this approach fails at determining suitable parameters, since new products require new evaluations. Therefore, in order to perform material flows as fast as possible, the physical constellation of every individual material flow has to be evaluated. For this purpose, physics simulation based on a physics engine offers potentials.

2.3 Physics simulation

The described effects that can lead to disturbances are based on dynamics and kinematics of rigid bodies (e.g. the workpieces and the respective elements of the material handling system). These phenomena can be simulated with physics engines [26], which is from now on referred to as physics simulation (also often called physics-based simulation). Physics engines are computer programs that allow a user to simulate and quantify the behavior of a set of rigid bodies over time as a result of external forces. Having their roots in computer graphics with the initial aim to efficiently compute physical occurrences for computer generated animations (e.g. video games), physics simulations have increasingly been applied in engineering applications. The advantage of using them is that after providing a set of defined constraints and physical attributes, many situations can be simulated without additional modeling efforts [18]. For example, after initial modeling of a material handling system, upcoming material flow processes can be simulated automatically by incorporating respective data about the transported objects and the adjustment of respective parameters. The basic workflow of physics simulation is as follows: After initialization, the considered objects (rigid bodies) are loaded into the simulation scene. Typically, these objects are represented by separate polygon meshes defined by the vertices, edges and faces of the individual object. These meshes can be derived from computer-aided design (CAD) drawings or specifications of workpieces. Before simulating, each object is assigned with physical properties like mass, inertia or friction coefficients. After definition of the properties, the interaction between the objects is simulated in discrete time steps [9]. Figure 3a) shows a typical simulation loop that is performed during each of these time steps of a physics simulation. In this Figure, first, the simulation detects any collisions between the objects (collision detection). For this purpose, the described mesh of every individual object serves as its respective collision geometry. After collisions have been detected, the respective contact points are registered. With respect to these contact points, physics equations regarding the motion of the individual objects are defined and solved in order to determine contact forces. This step helps to achieve proper friction simulation and to prevent objects penetrating each other and is referred to as contact handling. In the subsequent step, collision resolving handles different kinds of collisions: Contacts that have not occurred in previous time steps imply collisions that are accompanied by impulsive forces. These forces cause instant change of object velocities and are often handled separately from pre-existing contacts (e.g. an object resting on another). Finally, when all contact forces have been computed, the new positions and velocities are calculated via time integration before the described loop is performed again [4]. This is typically done with a frequency of at least 60 Hz. Due to the functional principle of physics simulation, the physical behavior of material flow processes can be simulated. In consequence, physics simulation can simulate and predict a range of different disturbances, as long as they are a result of those physical interactions. Examples for this type of disturbances are described in Section 2.2. Physics simulation has been applied in the past for simulation of material flows for virtual commissioning of planned production systems prior to their operation (see, for example, Zäh et al. [44], Reinhart et al. [33], Hoher et al. [21] or Alkan et al. [1]). It was indicated that using physics simulation to simulate material flows during the operation of a production system could result in decreased lead times [15] and reduced downtimes of material handling systems [44]. However, none of the existing approaches have proved a quantitative evaluation of such conclusions. In our previous work, the authors addressed this research gap with the aim of utilizing physics simulation to support the operation of material handling systems. The python library pyBullet was selected as a suitable environment to implement the envisioned simulation model [7]. The library pyBullet provides an extensive and adaptable framework to simulate the mechanical interaction of rigid bodies. Results of our previous work indicated that pyBullet is able to reliably predict the required types of phenomena. The resulting physics simulation model of the authors allowed to accurately simulate physical phenomena during material handling. This model was integrated into a digital twin concept which enables determination of suitable acceleration values for certain transported workpieces. This is done with a simulation model of an exemplary conveyor, shown in Figure 3b). The approach showed the potential of decreasing the required transport times with respect to the workpiece's physical attributes [19]. Summarizing, the simulation of material flows prior to their execution offers the potential of performing material flow processes faster and without load securing. By estimating respective parameters (e.g. velocity or acceleration), loads can be transported with increased yet safe velocity. This may result in improved material handling system utilization and decreased lead times. However, the systematic effect that this approach has on a production system level has not yet been investigated. For this purpose, the use of discrete-event simulation in combination with physics-based simulation is investigated in this paper.

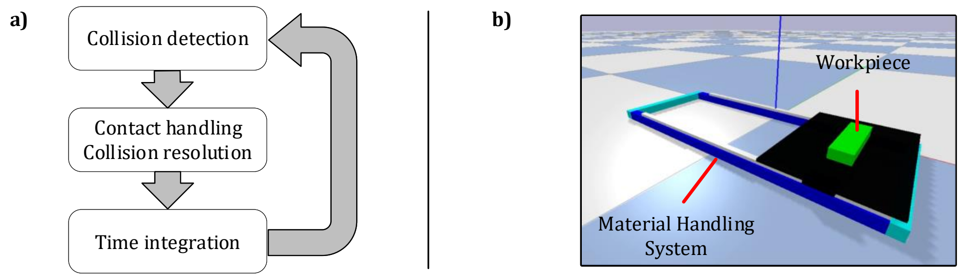

Figure 3 a) Simulation loop of a time step in physics simulations [4]; b) Physics simulation showing a workpiece on a conveyor [19].

2.4 Discrete-event simulation

Discrete-event simulation is a simulation technique, in which the temporal evolution of a system is modeled via state variables that change instantly at certain times. At each instant of time, the occurrence of certain discrete events changes the state of the overall system [30]. This allows modeling and simulation of the operation of complex systems and the tracking of individual resources. Various performance indicators can then be used to provide a comparison between different system parameters or alternatives, for example with regards to a system configuration. Discrete-event simulation is, therefore, suitable for simulating complex production systems [31] both in the planning as well as in the operational stage [29]. Several review papers (e.g. [29] and [28]) list numerous approaches that apply discrete-event simulation within manufacturing, e.g. for evaluating control strategies or to plan factory layouts. No approach however evaluates the performance of a production system with regards to the variation of physical attributes like velocity or acceleration within the material flow. Furthermore, besides a conceptual outline of the authors [17], no approach combines discrete-event simulation with physics simulation in order to analyze the effects of the latter on the performance of a production system. In current literature, few studies investigate the effect of material flow acceleration or velocity on the production system performance: Um et al. [39] incorporate AGV acceleration and velocity in the simulation of an FMS and conclude that especially velocity influences the throughput. Filz et al. [14] also vary AGV velocity within a matrix manufacturing system in their simulation study. The results indicate that the utilization of the manufacturing system increases with bigger AGV velocities. In these studies, the physics of material flows is however neglected and the physical applicability of the chosen velocities and accelerations is not considered. In addition, evaluating the effects of varying accelerations is not investigated as all previous studies regard the same values for all transports within one simulation scenario. Besides a conceptual outline of the authors [17], no previous approach combines discrete-event simulation with physics simulation in order to analyze the effects of physics-simulation-based individual accelerations on the performance of a production system.

2.5 Research Gap

After reviewing the state of the art, it can be concluded that characteristics of CPPS may lead to physically induced disturbances within material flow processes. This can result in accidents and can hamper the operation of a CPPS. Using physics simulation, the authors have shown that individual material flows can be simulated with the purpose of determining fast but safe acceleration and velocity values [19]. A promising approach is, therefore, to simulate each material flow process prior to its execution with the purpose of finding the maximum safe acceleration. The effect of these measures on the performance of a production system need to be investigated for the following reasons: Higher velocities and accelerations obviously decrease the time that is needed to transport one object from one place in the production system to another. The overall performance of a manufacturing system is however affected by more factors than just transport time (e.g. wait times). Changed velocities and accelerations might affect the behavior of the entire material flow, which can even influence other aspects such as wait time in buffers. Furthermore, product-individual material flow speeds and velocities omit the commonly chosen practice of selecting one equal speed configuration for all material flows. It needs to be analyzed how this inhomogeneous distribution of velocities and accelerations affects the overall production system performance. For the purpose of analyzing effect of certain organizational configurations on a production system, discrete-event simulation has been widely applied in manufacturing. This paper aims at addressing this research gap by performing a simulation study that combines physics simulation with discrete-event simulation. The approach to address this question is elaborated in the next Section.

3 Approach

This Section describes the approach that is chosen to investigate, whether the application of physics simulation can lead to improved production system performance, which is expressed through the measurement of throughput times and conveyor utilizations. Therefore, the approach consists of two simulation models (see Figure 4):

- A **discrete-event simulation model** is implemented that contains the structure and the control architecture of a customized small series production system. On this foundation, the operation of a production system over a certain amount of time can be simulated and different scenarios can be compared. The objects of interest in this case are not the value-adding process such as manufacturing or assembly, but the material flow processes in between these steps. The kinematical characteristics of these material flows, e.g. velocity and acceleration are to be varied in different scenarios. Finally, the effects that these different scenarios have on throughput time and conveyor utilization will be quantified.
- The discrete-event simulation is enhanced with a **physics simulation model** that is able to simulate the physics of the material flows in the production system. For this purpose, the maximum safe accelerations of all workpieces that are transported in the production system are determined. The resulting parameters are then transferred to the discrete-event simulation model.

The following Section describes the application of this approach in a simulation study.

4 Simulation study

4.1 Characteristics of the considered production system

The considered production system produces parts of transmission systems, which includes shafts, gears, plates, housings and blocks. Due to customization, a total range of 50 parts within these categories is being manufactured. All parts vary in terms of their physical attributes as a result of different shapes, mass distributions and surface structures. Furthermore, the parts require different process sequences. To enable this flexibility, the

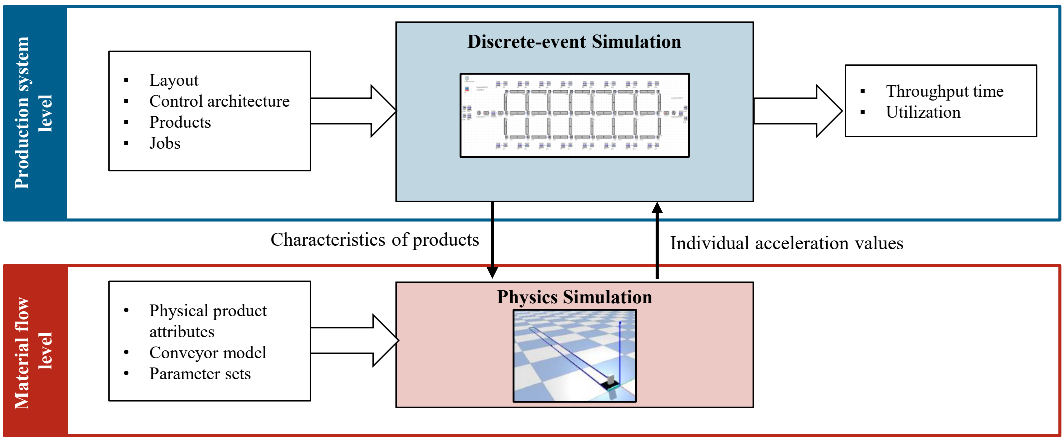

Figure 4 Approach.

production system consists of several workstations with universal processes like milling, turning or assembly. In the production system, an agent-based control architecture is implemented. Using an agent based control, parts, workstations and conveyors automatically find suitable production sequences. This makes the considered production system a CPPS [40]. Further flexibility is introduced through the material flow: The workstations are connected via a network of conveyors. These conveyors transport individual workpieces on workpiece carriers. The conveyors are driven by electric motors and all conveyors have a length of 6 m. When a workpiece is being transported, the respective conveyor accelerates the workpiece carrier with a constant acceleration “a” until a desired constant conveying velocity “v_c“ is reached. At the end of the conveyor, the pallet is decelerated with the same deceleration “-a”. The resulting kinematic characteristic of the conveyors is shown in Figure 5. The graph shows that with increased accelerations, v_c is reached faster, which leads to a higher average transport velocity and shorter transport times. This difference in required transport time between a $= 1\text{m/s}^2$ and a $= 3\text{m/s}^2$ ($v_c = 2$m/s in both cases) is indicated in the figure.

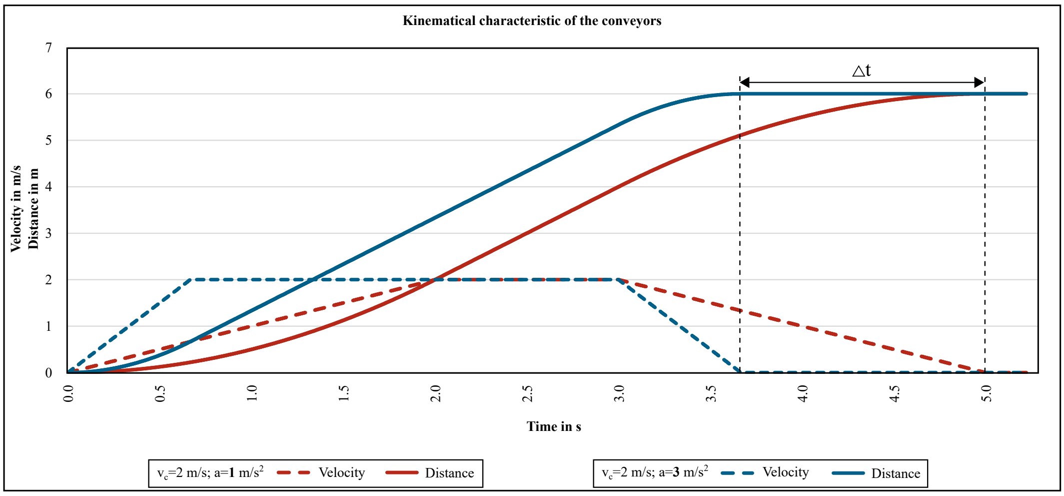

Figure 5 Kinematical characteristic of the conveyors.

4.2 Discrete-event simulation model

Implementing the discrete-event simulation included both the structure as well as the control architecture of the production system.

4.2.1 Structure of the discrete-event simulation model

The production system in the simulation model is a CPPS, in which the production of individual transmission components takes place. It is assumed that five fundamentally different product types are produced in the production system under consideration: Block, gear wheel, housing, plate and gear shaft. These product types are mutually characterized by different functions and geometries. Within a product type, the components are designed according to the customer's individual requirements, so that a distinction can be made between different characteristics. Thus, each component of a particular product type in turn has individual properties such as height and width. The product type distribution is listed in Table 1.

Table 1 Used part types and distribution.

Part type	**Number of individual components within part type**
Block	10
Gear wheel	11
Housing	10
Plate	6
Gear shaft	13
Sum	50

The individual components influence the selection of a motion profile, since the calculation of a component-specific acceleration is possible based on its geometry and other physical attributes like e.g. the friction coefficient between the part and the conveyor. During the simulation, each of the 50 individual components is produced four times in the production system under consideration. Here, production is carried out with batch size 1, so each job enters the production system at a different point in time. Consequently, a total of 200 jobs that lead to 200 individual components are performed in the simulation study. Furthermore, the components also influence the sequence of the steps to be performed. The production system comprises eight different production processes: Milling, turning, drilling, grinding, deburring, washing, forging and assembly. Each job is randomly assigned to one of 16 workstations (WS). Table 2 gives an overview over the WSs in the production system and the respective capabilities of the respective WS. For example, "Milling" can be performed on WS 1, WS 3 and WS 8, while "Washing" is exclusively performed on WS 9.

In order to enable transport between the individual WSs, networked conveyors are used. Customer-specific production with different routings and correspondingly different routes through the production system requires the use of decentralized control. Accordingly, the conveyors themselves determine the route that the respective workpieces take through the system. The workpieces are placed on a flat workpiece carrier for transport, which in turn moves through the production system on conveyors. Since individualized fixtures or recesses for inserting and securing the workpieces are very costly in customized production and the alternative of fixing the workpieces on the workpiece carrier takes a certain amount of time, the components are instead secured by selecting the suitable acceleration profile. Consequently, the appropriate values for acceleration have to be chosen with regards to

Table 2 Processes and respective workstations.

Process	workstation
Milling	WS 1, WS 3, WS 8
Turning	WS 2, WS 4, WS 5
Drilling	WS 6, WS 7,
Grinding	WS 12
Deburring	WS 11
Washing	WS 9
Forging	WS 10
Assembly	WS 13, WS 14, WS 15, WS 16

the transported workpiece to prevent it from tilting or slipping off the workpiece carrier without securing them. All conveyors that connect the WSs are assigned the length of 6 m. The conveyors are connected by transfer devices, which can move the loaded workpiece carriers to the next conveyor as well as to the adjacent WS. Since only one workpiece carrier can be on a conveyor at a time, buffers are placed in front of the respective WSs to avoid conveyor downtimes due to blocking. The buffers follow the first-in-first-out principle and transfer the workpiece with the longest waiting time immediately when the corresponding WS becomes vacant. A simplified overview of the production system is depicted in Figure 6. As shown in this Figure, individual WSs are arranged in an O-shape connected by a system of rectangularly structured conveyors. Individual stations with odd numbers are located in the lower area, whereas the remaining stations are located in the upper area. A centrally running conveyor line and cross-connections between the individual stations enable a greater variety of transport routes. The workpieces enter the production system through the source (left) and leave it again via the sink (right) after completing the last production step.

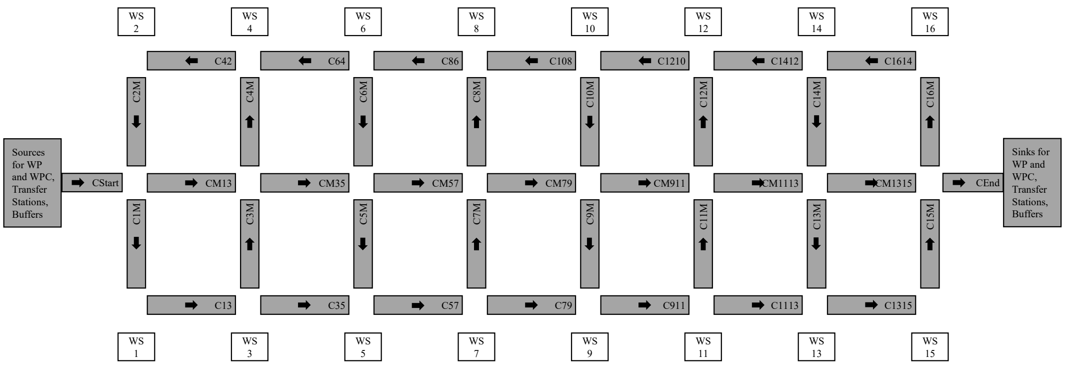

Figure 6 Simplified overview over the production system structure (transfer stations and buffers not included).

The described production system is implemented as a runnable discrete-event simulation model with the help of the simulation software SIEMENS Plant Simulation version 15.0 [35]. The implemented structure of the production system in the simulation model is shown in Figure 7. In order to design a runnable model from the simulation model, it is further necessary to control the working steps to be performed. This is outlined in the following subsection.

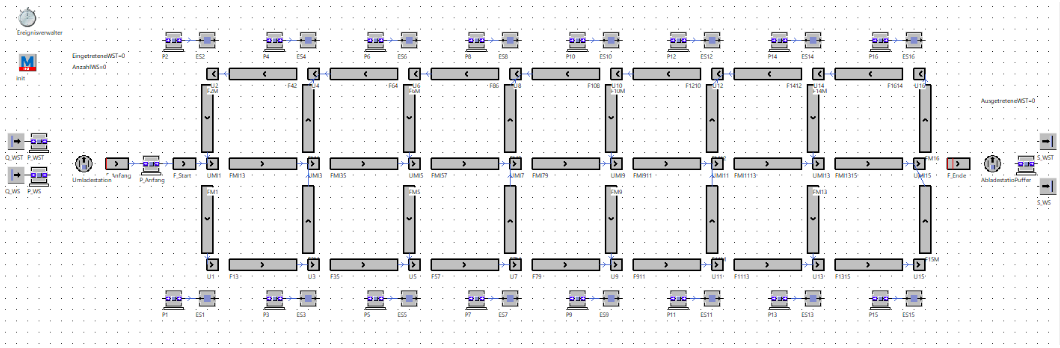

Figure 7 Structure of the production system in the implemented discrete-event simulation model.

4.2.2 Control of the discrete-event simulation model

To control the processes of the described production system, several methods and tables were added to the described simulation environment. In this context, methods refer to pieces of executable code that are being triggered by certain events (e.g. a conveyor passing a certain point), while tables are used to provide numerical values and other information that is required to run a discrete-event simulation. Plant Simulation requires different methods and tables which ensure the processing of the component-specific work plan as well as the coordination of the material flows. For the sake of clarity, all tables are preceded by the letter "T" and all methods by the letter "M". In the following, all methods that are utilized in the simulation model are explained. In addition, the most important method for the control is described with the help of a flow chart. The methods can be integrated as input or output control modules of the individual blocks and are executed before the workpieces enter or leave the corresponding block. In this context, a module is understood to be a source, sink, an individual station, a conveyor, a converter as well as a transfer or an unloading station. The components first enter the production system through the source S_{WS}. For this purpose, each of the 200 components is randomly assigned an entry time in the table $\mathrm{T}_{\mathrm{Source}}$ using the method $\mathrm{M}_{\mathrm{init}}$, for which an equally distributed random number is generated in the interval from 1 min to 200 min. This means that on average one new production order with a workpiece to be produced enters the system every minute. The workpiece carriers that are necessary for the transport of the workpieces are generated within the first 100 s in the source $\mathrm{S}_{\mathrm{WPC}}$ and then wait in buffer $\mathrm{B}_{\mathrm{WPC}}$ for a workpiece to be loaded. As soon as a workpiece is generated, the method $\mathrm{M}_{\mathrm{WPC}}$ provides a workpiece carrier on which the workpiece is transported through the production system. The workpiece is loaded onto the workpiece carrier via the reloading station and the conveyor $\mathrm{C}_{\mathrm{Start}}$. In combination with method M_{WP}, the output control $\mathrm{M}_{\mathrm{CStart}}$ ensures that the name of the loaded workpiece can be accessed. To do this, the name is entered to the $\mathrm{T}_{\mathrm{count}}$ table, which is necessary for processing the individual work plan. The workpiece and its carrier wait in the buffer $\mathrm{B}_{\mathrm{Start}}$ until the first conveyor section $\mathrm{C}_{\mathrm{Start}}$ is free and both can enter the actual production system. When they enter, the number of workpieces in the system n_{WP} is increased by one using the method "$\mathrm{M}_{\mathrm{nWP}}$" in order to improve the traceability of the production process. In the following, the terms "workpiece" and "workpiece carrier" are used analogously. What is always meant here is the combination of a workpiece and its workpiece carrier, which pass through the production system together from the transfer station to the unloading station. When entering the area of the WSs, the workpiece carrier is transported to the first transfer station. Like all other conveyors and transfer units, the first transfer unit has the method

M_{av} assigned as input control. According to the examined movement profile with velocity and acceleration, the appropriate values from the tables $T_{acceleration}$ and $T_{velocity}$ are set for the transfer unit or conveyor and result from physics simulation as described in the following subsections. When leaving the transfer unit, $M_{Destination}$ is called up, which is decisive for the processing of the work plan and the control of the workpiece carriers by the production system. This method can be seen as the most important control method of the present simulation model and in this case, it implements the decentralized control of the conveyors by the production system in the simulation model. The control system integrated with each conveyor and transfer unit consists of two parts: In the first part, the next processing station for the present workpiece carrier is determined by means of several table comparisons. In the second part the transfer to the next conveyor is carried out according to the destination. As shown in the flow chart in Figure 8 , the first part checks whether any work steps are still pending. If this is not the case, the conveyor C_{End} is selected as the next destination and the workpiece carrier moves to the sink. Otherwise, the next work step and the corresponding processing station are selected by comparing several table values. Now all possible processing stations are checked for their assignment. The station first recognized as free is selected as destination and entered in the table $T_{NextDestination}$. If all stations are occupied, the first possible station is again selected as destination and waiting times are accepted.

The second part of the method $M_{Destination}$ is based on three binary questions:

1. On which module is the workpiece carrier currently located?
2. What is the next destination of the workpiece carrier?
3. How must the workpiece carrier be transferred in order to reach its destination by the shortest route?

To implement this method, corresponding work plans are necessary, which are stored for each component in the table $T_{Properties}$. Table 3 shows an example of the working plan for a housing workpiece. Via T_{WS}, the corresponding individual stations are assigned to the work steps. For the component in question, the milling step must first be carried out, which can be performed on the stations “WS 1”, “WS 3” or “WS 8” according to the information in Table 2.

Table 3 Exemplary work plan.

Step number	Process
1	Milling
2	Drilling
3	Deburring
4	Washing
5	Assembly

To select a station, the method $M_{Destination}$ is used and the cycle described in Figure 8 is performed: First, the method checks whether station “WS 1” is free. Assuming that this is the case, the second part of the method decides on which conveyor the workpiece carrier is transferred. Following the principle of the shortest way, the workpiece carrier is transferred to the conveyor “CM1”. If again station “WS 2” or “WS 4” were the next destination, the workpiece carrier would be transferred to conveyor “CM13”. Via the conveyors (where again M_{av} selects the respective acceleration-velocity constellation), the transfer units and the upstream buffer, the workpiece is brought to the corresponding WS. There, in addition to processing, the current individual station is entered in T_{Count} via M_{Count} as the input control of the individual station. This table is used to enable a comparison between the

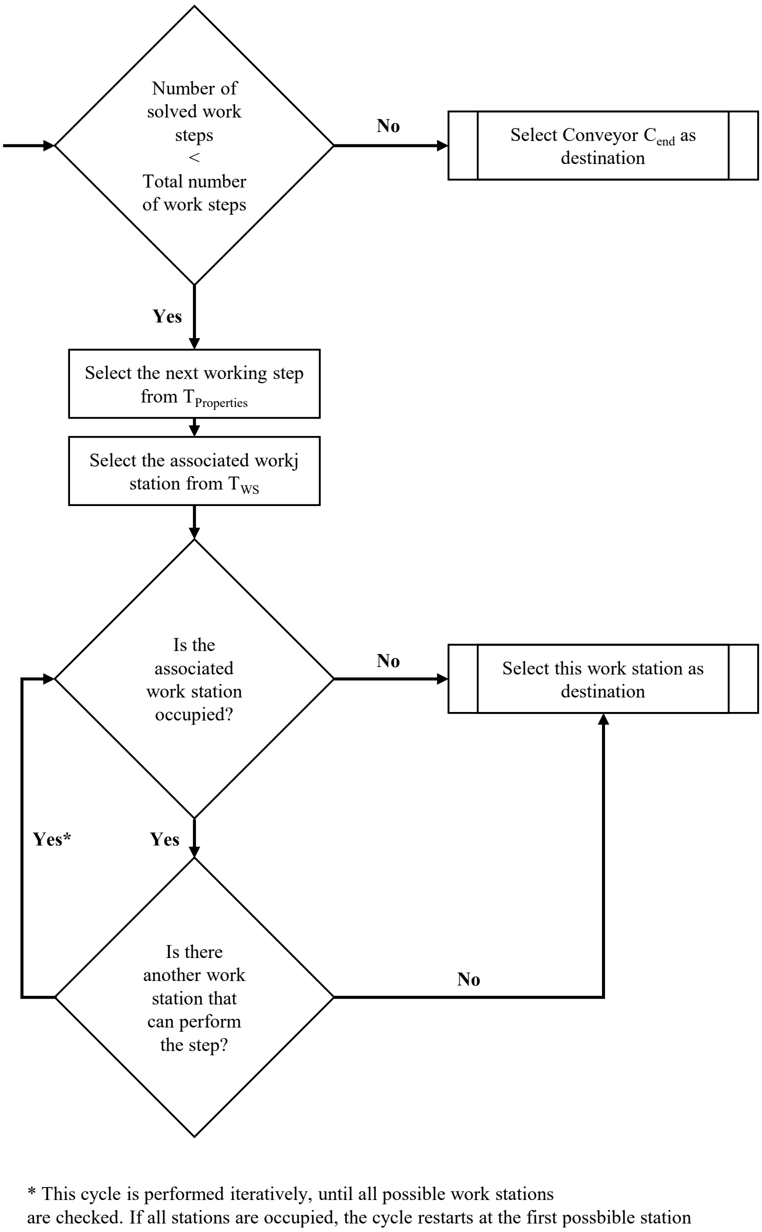

Figure 8 Flow chart of $\mathrm{M}_{Destination}$.

number of steps already completed and the total number of steps in $\mathrm{M}_{\mathrm{Destination}}$. The method $\mathrm{M}_{\mathrm{OutputWS}}$, which is integrated into the individual stations as output control, removes the current destination from $\mathrm{T}_{\mathrm{NextDestination}}$ and transfers the workpiece carrier to the next conveyor. This sequence of operations is repeated until all steps of a work plan are completed and the workpiece carrier is directed to the conveyor $\mathrm{C}_{\mathrm{End}}$. Via the input control of this conveyor, the number of workpieces in the system n_{WP} is reduced by 1 with $\mathrm{M}_{\mathrm{nWP}}$. The output control $\mathrm{M}_{\mathrm{EvaluationWS}}$ enters the key figures required for the evaluation in relation to the utilization of the WSs and conveyors in the tables $\mathrm{T}_{\mathrm{EvaluationWS}}$ or in $\mathrm{T}_{\mathrm{EvaluationConveyors}}$ as soon as the processing of all 200 workpieces has been completed. Afterwards, the finished workpiece is taken from the workpiece carrier via the unloading station and the downstream buffer. Both are conveyed to their respective sinks using the M_{Buffer} method. The method $M_{MEvaluation\_throughput}$ computes and enters the key resulting figures related to the actual workpiece in the table $T_{Evaluation\_throughput}$. The discrete-event simulation model performs the operation of the production system. As described above, this requires product-individual acceleration values that are derived with a physics simulation model which is described in the next Subsection.

4.3 Physics simulation model

In order to determine optimal parameters, each material flow process needs to be simulated using physics simulation. This requires physical models that consist of the respective material handling systems as well as of the transported work pieces. Regarding the material handling systems, pallet-type conveyors were used. These conveyors use workpiece pallets that are conveyed on rails and are used to carry the workpieces. To determine the physical behavior of components during transport, it is sufficient to model just one instance of the conveyor, as all conveyors in the production system are alike. Therefore, the conveyor was modeled in pyBullet including the length of the conveyor track and the area of the load bed. Furthermore, a control module was implemented that is able to perform material handling processes with specific parameters of “a” and “v_c” according to the kinematics of Figure 5. In addition, physics simulation models of the produced components (workpieces) were created, including attributes like mass, inertia or friction. For each manufactured component, the ideal transport parameters are defined. For this purpose, the previously described and validated physics simulation model was adapted [16]. Figure 9 shows an exemplary workpiece that is being transported on the conveyor model. Each part that is being produced and transported in the production system was simulated within the physics simulation environment.

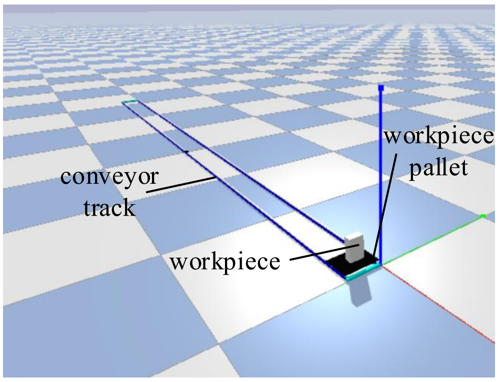

Figure 9 Physics simulation model of the conveyor.

In order to determine the optimal acceleration for each component, a predictive rule-based approach as described in [19] was used (see Figure 10). Using physics simulation, the effect of different acceleration values on the stability of the workpiece is investigated. If the simulation suggests that this stability cannot be maintained for the respective configuration (e.g. the workpiece tips over due to acceleration), this consequence is considered a disturbance and the selected acceleration value cannot be used for the real process. Determining the chosen acceleration is achieved using an iterative approach. For this purpose, a list of different acceleration values from 0.5 to 10.0 m/s² in steps of 0.5 m/s² is generated. For each acceleration value, a simulation run is performed, evaluating the effects on the stability of the transported workpiece. All accelerations that resulted in a disturbance are neglected. Within the acceleration values that did not cause any disturbance, the highest value is selected as the acceleration for the respective component. This resulted in a list of components and respective maximum acceleration values. The contents of this list are given in Table 4 and serve as input for the discrete-event simulation in the subsequent Section.

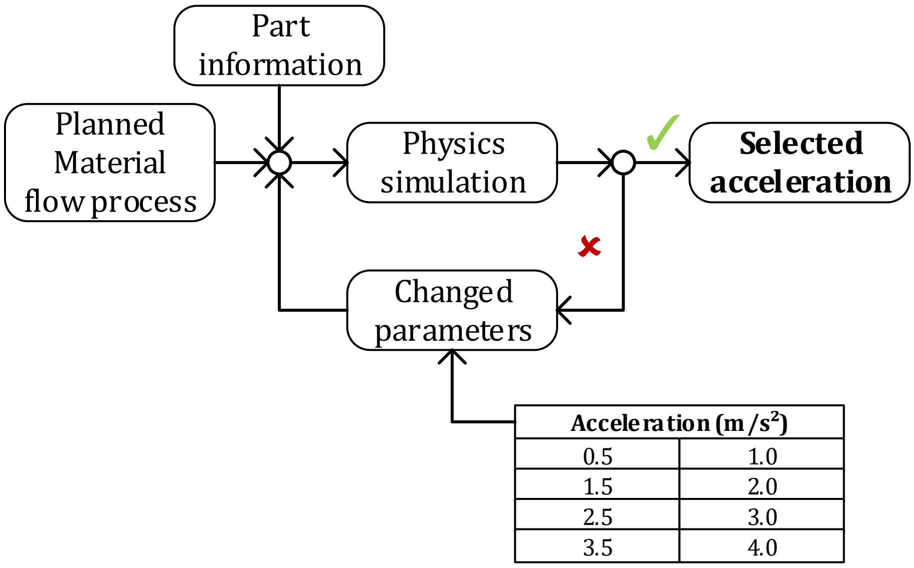

Figure 10 Logical sequence for determining suitable acceleration values.

Table 4 List of simulated components (Id) and the respective identified maximum acceleration value in m/s².

Id	a_{ind}	Id	a_{ind}	Id	a_{ind}	Id	a_{ind}	Id	a_{ind}
Block01	2.0	Gear01	4.5	Housing01	5.5	Plate01	8.5	Shaft01	2.5
Block02	2.5	Gear02	7.5	Housing02	2.5	Plate02	4.5	Shaft02	2.5
Block03	2.5	Gear03	5.5	Housing03	6.5	Plate03	7.5	Shaft03	2.5
Block04	2.5	Gear04	8.5	Housing04	6.5	Plate04	3.5	Shaft04	2.0
Block05	2.0	Gear05	4.5	Housing05	8.5	Plate05	7.5	Shaft05	2.0
Block06	4.0	Gear06	8.5	Housing06	3.5	Plate06	4.5	Shaft06	7.5
Block07	5.0	Gear07	3.5	Housing07	4.5			Shaft07	5.5
Block08	3.0	Gear08	5.5	Housing08	3.5			Shaft08	2.0
Block09	2.5	Gear09	5.5	Housing09	3.5			Shaft09	2.5
Block10	2.5	Gear10	5.5	Housing10	8.5			Shaft10	2.0
		Gear11	7.5					Shaft11	4.5
								Shaft12	5.5
								Shaft13	7.5

4.4 Connection of the models

As described before, the discrete-event simulation model performs production tasks that are performed on various WSs. The transports between those WSs are performed via conveyors. Based on a table that contains physical properties of the 50 produced components, physics simulations are performed and the acceleration parameters are derived as described in Section

4.3. The component-individual physics simulation results shown in Table 4 are exported to an excel file, which can be imported into SIEMENS Plant Simulation. Here, the simulation-based values for acceleration (a_{ind}) are entered in the $T_{acceleration}$ table and are used for the discrete-event simulation.

4.5 Simulation run and results

In order to analyze the effect of acceleration and velocity, 16 scenarios were considered, that are all characterized by a specific acceleration-velocity-pairing. Besides considering the parameters that resulted from the physics simulation (Scenarios 13-16, values from Table 4), fixed accelerations from 1 to 3 m/s² were also incorporated (Scenarios 1-12). All scenarios are summarized in the following Table 5.

Table 5 Simulation scenarios.

		Acceleration in m/s²			
		1	**2**	**3**	**Individual acceleration**
Velocity in m/s	**0.5**	1	5	9	13
	1.0	2	6	10	14
	1.5	3	7	11	15
	2.0	4	8	12	16

For all scenarios, the respective values for acceleration and velocity were passed to the respective tables to be processed within the discrete-event simulation model. Within each scenario, the throughput times of all 200 jobs are analyzed and the mean throughput time is calculated. In order to reduce the impact of random effects, a basic principle in discrete-event simulation is that an increase in the number of simulation runs and a longer simulation duration leads to improved quality of results. This is due to the fact that with a larger sample size the confidence interval becomes smaller and thus the inaccuracy about the exact location of the target value is reduced [42]. A commonly used number of simulation runs is 10 [25]. In this analysis, this value is doubled and therefore 20 simulation runs are performed per scenario. In order to consider random influences on one hand and to make the results comparable on the other hand, the random seed starting value in Plant Simulation, which starts with 1, is increased by one with each repetition. Therefore, randomized orders of incoming jobs are considered in the 20 runs per scenario. Afterwards, the average throughput and utilization values from the 20 runs per scenario are calculated. Figure 11a) shows the resulting throughput times for the 16 scenarios, clustered by values for same acceleration.

It becomes clear that with constant acceleration, increasing the conveyor velocity leads to a significant reduction in the throughput time. The influence of acceleration becomes clearer in Figure 11b), where the diagram shows the throughput time, clustered by values of same velocity. It can be seen in this Figure that in a class with constant velocity, the average throughput time decreases when the acceleration is increased. Comparing the four velocity clusters with each other, it becomes clear that such a decrease compared to the slowest acceleration scenario of a class (scenario 1, 2, 3 or 4) becomes larger with increasing velocity. Consequently, in the cluster $v_c = 2$ m/s, the difference between slowest acceleration and component-specific acceleration (see Table 4) is significantly greater than in the cluster $v_c = 0.5$ m/s. Besides the comparison between scenario 1 and 5, all relevant differences can be seen as significant (see Appendix A). Within a cluster of equal velocity, the scenario with

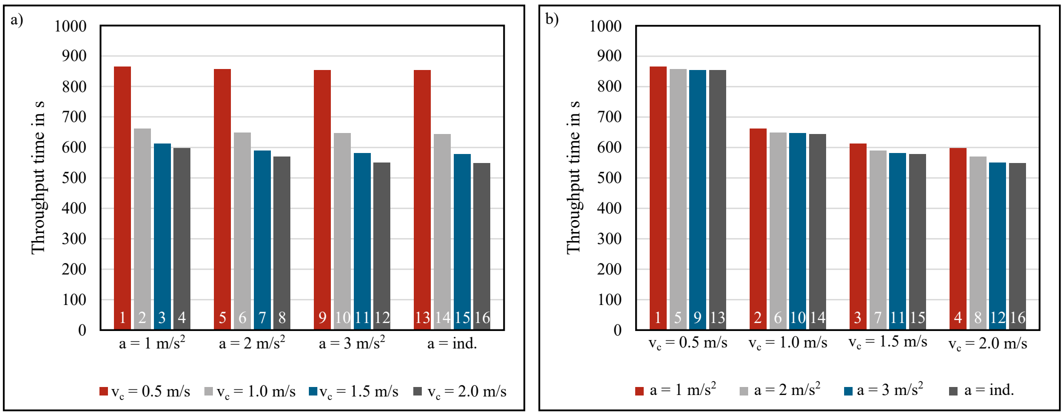

Figure 11 Resulting throughput times; a) clustered by acceleration; b) clustered by velocity.

component-specific acceleration using the physics simulation leads to the shortest processing time in each case. Overall, the selection of the motion profile in scenario 16 ($v_c = 2$ m/s and a = component-specific) leads to the shortest processing time of all scenarios. It can be concluded, that the influence of high accelerations becomes especially important with high transport velocities. In addition to throughput, capacity utilization is another commonly chosen performance indicator in a production system. This quantity describes the ratio of actual to maximum possible utilization of a resource [32]. In this context, the capacity utilization of the conveyors with regards to velocity and acceleration were analyzed. The results are shown in Figure 12.

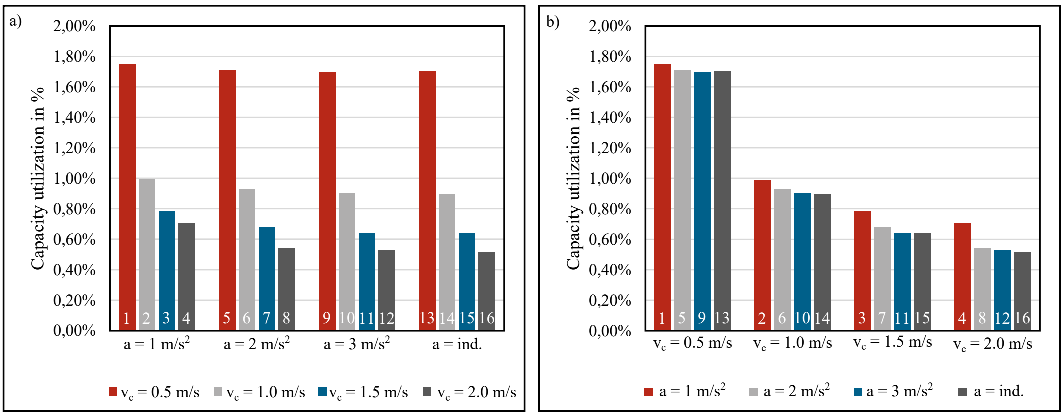

Figure 12 Resulting capacity utilization of conveyors: a) clustered by acceleration; b) clustered by velocity.

The choice of the acceleration-velocity constellation has a significant effect on the conveyor utilization. Figure 12a) shows significant changes in the utilization of the conveyors with increasing velocity. As the bar graphs in this Figure show, each increase in velocity leads to a reduced utilization of the conveyors, which means that they have higher capacities for further production orders. Within a cluster of constant acceleration, in particular the doubling of the velocity from $v_c = 0.5$ m/s to $v_c = 1$ m/s leads to a strong effect on the capacity utilization, which is almost reduced by half. A similar effect can be observed when doubling the velocity from $v_c = 1$ m/s to $v_c = 2$ m/s, which emphasizes the positive effect of a possible technical realization of increased conveyor velocities. If the utilization of the conveyors is clustered by variable accelerations at constant velocities, an influence of the acceleration is observed (see Figure 12b)). Every increase in acceleration results in a lower utilization of the conveyors. Although the differences are not as great as between the velocity variations, a clear tendency can be seen here as well. Apart from the velocity class $v_c = 0.5$ m/s, the correlation can be described as significant. In this case, the effects of acceleration on the utilization of the conveyors become stronger with increasing velocity. As a consequence, in the case of a component-specific acceleration (see Table 4) and a velocity of $v_c = 2$ m/s (scenario 16), the lowest utilization is recorded. All differences regarding capacity utilization can be seen as significant, excluding the differences in the $v_c = 0.5$ m/s cluster (see Appendix A). In conclusion, the results indicate that the choice of conveyor velocity has an influence on the throughput time and its utilization. With increasing velocity, the throughput time can be reduced and the utilization of the conveyors can be lowered. Also, the influence of acceleration can be recognized. With increasing acceleration, both the throughput time and the utilization of the conveyors can be reduced. In general, the effect of acceleration on both target variables is less than with increasing velocity, but is clearly visible and significant in the figures. In this respect, the alignment of the acceleration to workpiece-specific conditions in particular leads to the lowest values in terms of throughput time and conveyor utilization compared to other acceleration variants. This indicates that using physics simulation to determine component-specific accelerations can be beneficial to the operation of a production system.

4.6 Discussion of results

The results indicate that the velocity of the material flow strongly influences throughput time in a production system. It becomes obvious that the constant velocity v_c is the most important value that has the largest impact on throughput time. In comparison, the effect of the accelerations which are calculated with physics simulations seems small. However, the results show that the effect of high accelerations becomes stronger with higher velocities. This seems reasonable, since high conveying speeds can only be reached quickly with an adequate acceleration. This is especially true on short transport distances. Therefore, achieving shorter material flow times benefits from high velocities but is also enabled by high accelerations.

It can therefore be concluded that physics simulation can provide a substantial improvement for material flows in future production systems: Using adequate models of material handling systems and transported components, the potentials of faster material flows can be exploited, resulting in better production system performance.

In order to reduce the modeling efforts, all components were assumed to be physically complete from the beginning of their production. This was done to reduce the physical modeling efforts, since otherwise, a physical model of each manufacturing sub-step (e.g. raw parts and semi-finished components) of all 50 products would have to be created. This is a simplification, since in a real scenario, the physical attributes of a product may change in the course of a manufacturing process, for instance through removed material and hence changed mass distribution. Overcoming this simplification would have included to generate three-dimensional (e.g. CAD) data about the geometry of every sub-step, along with the respective mass distribution (e.g. by calculating the removed mass during a milling process) and friction coefficient. While this can be performed manually by assessing every manufacturing step and the effects on the physical properties of a component, future research could investigate the utilization of respective simulation or calculation methods (e.g. material removal simulations) that can derive physical models of sub-steps automatically. Further aspects can be added to the simulation study to represent the complexity that is incorporated in industrial settings. The kinematical characteristic (see Figure 5) might be extracted from real conveyors, which might show non-linear acceleration. In addition, physical obstacles like curves or slopes that are often found in real factories can be added to the conveyors. Additionally, machine failures or maintenance times can be added to the discrete-event simulation. This also affects conveyors which might need to be repaired as well, which results in a limited availability.

Furthermore, exploiting the operational benefits of faster material flows in real production systems is connected to certain challenges. It is likely, that higher velocities and accelerations lead to higher energy consumptions of the material handling systems which need to be considered. Furthermore, compared to the slow but steady operation of most current material handling systems, the alternating operation that is connected to component-specific accelerations needs to be incorporated during the design of these systems (e.g. drives and bearings).

5 Summary and outlook

Material flows that are performed by material handling systems account for a significant percentage of the manufacturing cost of a product. For preventing disturbances as a result of strong accelerations and inertia forces, material flows are usually performed at comparably low velocities and accelerations. As a result, non-value-adding transport times increase throughput times and block conveyors. Despite the safety advantages, potentials to improve the operation of a production system by faster material flows are mostly unexploited. Physics simulation using physics engines has indicated the potential of determining component-individual accelerations. However, the effects on the performance of a production system have not been investigated in the past.

In order analyze these effects, this paper analyzed the influence of velocity and acceleration on throughput time and capacity utilization of conveyors within a production system. For this purpose, a discrete-event simulation was combined with a physics simulation. The results indicate that throughput times can be significantly reduced by choosing faster velocities for material handling systems. The influence of accelerations was found to be smaller, however it became increasingly greater with higher velocities. This means that high accelerations serve as an enabler to allow for performance optimizations through high velocities. A consideration of component-individual accelerations therefore seems useful when operating material handling systems with high velocities.

Despite the potential benefits through faster material flows, the optimization of routing and scheduling still plays a crucial role in production system operation. It seems promising to further investigate the described coupling of discrete-event and physics simulation with the goal of optimizing routing and scheduling along with ensuring the physical feasibility of the material flows. Further research also needs to evaluate the barriers of implementing the investigated component-individual acceleration control in a factory environment. Furthermore, sub-steps of manufactured components can be included within the physics simulation (see Section 4.6).

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A Significance analysis

In order to determine significance, Welch's-t-test is applied (see [25]). The confidence interval (CI) between two results was calculated according to Equation 1:

$$CI = \overline{X_1} - \overline{X_2} \pm t_{f,1-\frac{a}{2}} \cdot \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \tag{1}$$

Here, $\overline{X_1}$ and $\overline{X_2}$ are the mean values of the respective scenarios regarding throughput time and utilization. s denotes the standard deviation, while n stands for the number of samples (4000). The two-tailed t-value was calculated with the degrees of freedom f according to Equation 2. Tables 6 and 7 show the significance analysis results. The difference is seen as significant, if the CI does not include 0.

$$f = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{(n_1-1)} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{(n_2-1)}} \tag{2}$$

Table 6 Significance analysis for throughput time.

Compared scenarios	Lower endpoint welch interval	Upper endpoint welch interval	Significant difference?
1 vs. 2	193.49	212.27	yes
1 vs. 3	243.04	261.68	yes
1 vs. 4	257.06	276.75	yes
5 vs. 6	200.21	218.68	yes
5 vs. 7	258.63	277.00	yes
5 vs. 8	278.37	298.00	yes
9 vs. 10	198.27	217.11	yes
9 vs. 11	263.73	281.94	yes
9 vs. 12	294.85	313.40	yes
13 vs. 14	200.56	219.50	yes
13 vs. 15	267.38	285.44	yes
13 vs. 16	295.75	314.06	yes
1 vs. 5	-3.06	17.87	no
1 vs. 9	0.63	21.48	yes
1 vs. 13	0.54	21.45	yes
2 vs. 6	5.97	21.97	yes
2 vs. 10	7.60	24.12	yes
2 vs. 14	9.85	26.43	yes
3 vs. 7	15.00	30.71	yes
3 vs. 11	23.71	39.34	yes
3 vs. 15	27.35	42.73	yes
4 vs. 8	19.53	37.84	yes
4 vs. 12	39.66	56.89	yes
4 vs. 16	40.53	57.46	yes

Table 7 Significance analysis for capacity utilization.

Compared scenarios	Lower endpoint welch interval	Upper endpoint welch interval	Significant difference?
1 vs. 2	0.0067	0.0084	yes
1 vs. 3	0.0089	0.0104	yes
1 vs. 4	0.0096	0.0112	yes
5 vs. 6	0.0070	0.0087	yes
5 vs. 7	0.0095	0.0111	yes
5 vs. 8	0.0109	0.0124	yes
9 vs. 10	0.0071	0.0088	yes
9 vs. 11	0.0098	0.0113	yes
9 vs. 12	0.0110	0.0125	yes
13 vs. 14	0.0073	0.0089	yes
13 vs. 15	0.0099	0.0114	yes
13 vs. 16	0.0111	0.0126	yes
1 vs. 5	-0.0006	0.0013	no
1 vs. 9	-0.0005	0.0014	no
1 vs. 13	-0.0005	0.0014	no
2 vs. 6	0.0001	0.0012	yes
2 vs. 10	0.0003	0.0014	yes
2 vs. 14	0.0004	0.0015	yes
3 vs. 7	0.0006	0.0014	yes
3 vs. 11	0.0010	0.0018	yes
3 vs. 15	0.0011	0.0019	yes
4 vs. 8	0.0013	0.0020	yes
4 vs. 12	0.0014	0.0021	yes
4 vs. 16	0.0016	0.0023	yes