

Reihenfolgestabilität in der automobilen Variantenfließfertigung

Mareike Müller

KATHOLISCHE UNIVERSITÄT  
EICHSTÄTT-INGOLSTADT  
Wirtschaftswissenschaftliche Fakultät



Dissertation zur Erlangung des Grades  
Doktor der Wirtschaftswissenschaften (Dr. rer. pol.)  
über das Thema

Stabilized mixed-model assembly lines in automotive production  
Reihenfolgestabilität in der automobilen Variantenfließfertigung

Zusammenfassung der Einzelbeiträge der kumulativen Dissertation gemäß §5 Abs. 3 S.3 der  
Promotionsordnung der Wirtschaftswissenschaftlichen Fakultät der Katholischen Universität  
Eichstätt-Ingolstadt vom 1. Oktober 2015

Mareike Müller (M.Sc.)

Erstgutachter

Prof. Dr. Heinrich Kuhn

Zweitgutachter

Prof. Dr. Thomas Setzer

## Zusammenfassung

Gegenstand der vorliegenden kumulativen Dissertation ist das Thema Stabilität in der automobilen Variantenfließfertigung. Die Arbeit umfasst die nachfolgend genannten vier wissenschaftlichen Einzelbeiträge:

1. Müller, Mareike, Lehmann, Marcel und Kuhn, Heinrich (2020): **Measuring sequence stability in automotive production lines.** *Veröffentlicht im International Journal of Production Research am 23.07.2020, DOI: 10.1080/00207543.2020.1790685*
2. Müller, Mareike und Kuhn, Heinrich (2020): **Shared buffer in stabilized automotive production systems.** *Working Paper, Target Journal: Computers & Industrial Engineering*
3. Lehmann, Marcel, Müller, Mareike und Kuhn, Heinrich (2020): **Assembly line feeding concepts and supermarket allocation in automotive production.** *Working Paper, Target Journal: Journal on Transportation and Logistics*
4. Müller, Mareike (2020): **Management of buffer systems in automotive stabilized production networks - a qualitative analysis.** *Veröffentlicht im Social Science Research Network (SSRN) am 29.09.2020, Abstract ID 3701532*

In der Automobilindustrie ermöglichen flexible Fertigungslinien die Produktion variantenreicher, individuell ausgestatteter Fahrzeugmodelle mit kleinem Produktionsvolumen bis hin zur Losgröße eins. Dies verursacht einen zunehmenden logistischen Aufwand, da die Anzahl unterschiedlicher Teile und Komponenten stark ansteigt. Um Fertigungslinien weiterhin effizient mit Teilen zu versorgen, werden neue Produktionsstrategien und Logistikkonzepte entwickelt. Die Anwendung der Auftragsfertigung und die frühzeitige Festlegung der Fertigungsreihenfolge ermöglicht die Umsetzung von bedarfs- und reihenfolgesynchronen (JIS) Anlieferungsstrategien sowie die Einrichtung von Supermärkten an den Fertigungslinien. Basis hierfür ist eine konstante Fertigungsfolge nach der sich die internen sowie externen Logistikprozesse ausrichten. Dies erfordert eine hohe Prozessstabilität, die kontinuierlich gemessen werden muss. Aufgrund von stochastischen Prozesszeiten, Reihenfolgeverwirbelungen und Stauwirkungen im Produktionsfluss wird die Stabilität gemindert. Durch die gezielte Allokation von Puffern lassen sich diese Effekte reduzieren. Diese Arbeit untersucht Kennzahlen zur Messung von Stabilität, die Allokation von Puffern sowie Versorgungsstrategien von JIS Teilen in der reihenfolgestabilen Automobilproduktion.

## Beitrag 1

### *Measuring sequence stability in automotive production lines*

(Müller et al., 2020)

Automobilhersteller bewerten die Leistung ihres Produktionssystems, um die Effizienz und langfristige Wettbewerbsfähigkeit der Produktionsstandorte zu gewährleisten. Voraussetzung hierfür ist, dass die Produktion über ein wirksames Steuerungskonzept verfügt und sich dieses durch aussagekräftige Messgrößen beurteilen lässt, die den Aufwand von betrieblichen Prozessen abbilden. Eine relevante Kenngröße um den effizienten Betrieb einer reihenfolgestabilen Variantenfließfertigung zu bewerten ist die Stabilität des Produktionsprozesses. Zwei relevante Bewertungskriterien sind der Aufwand für die Materialversorgung der Fertigung sowie die erforderliche Pufferkapazitäten zur Wiederherstellung der Reihenfolgestabilität. Indikatoren zur Quantifizierung und Visualisierung der Stabilität in der Variantenfließfertigungen wurden in der existierenden Literatur bisher nur unzureichend untersucht. Die angewendeten Kennzahlen werden oft nicht spezifiziert oder referenziert und es fehlt eine einheitliche Notation.

In dem Beitrag „Measuring sequence stability in automotive production lines“ werden sechs Leistungsindikatoren, die in der Praxis und Literatur Anwendung finden, zur Bewertung der Reihenfolgestabilität analysiert. Die wesentlichen Faktoren zur Gewährleistung einer reihenfolgestabilen Produktion werden erläutert und die Grenzen klassischer Produktionskennzahlen aufgezeigt. Um das Leistungsverhalten und die Effektivität der sechs Stabilitätskennzahlen zu bewerten, folgt die Durchführung einer Studie, bei der die Relevanz der Kennzahlen bezüglich der Abbildung des Aufwands betrieblicher Prozesse eingestuft wird. Keine der vorgestellten Kennzahlen reicht einzeln angewendet aus, um den Grad der Reihenfolgestabilität mit allen erforderlichen Aspekten zu bestimmen. Eine Kombination aus drei Kennzahlen wird benötigt, um die Stabilität des Produktionssystems für operative Aktivitäten und Entscheidungen zielführend darzustellen. Eine Kennzahl bildet den Aufwand der Materialversorgung ab und zwei quantifizieren die erforderliche Pufferkapazität. Die in der Praxis am häufigsten verwendete Kennzahl ist nicht unter den drei Relevanten. Die drei signifikanten Kennzahlen werden an einem Datensatz aus der Produktion eines deutschen Automobilherstellers angewendet. Herausforderungen, die bei der Implementierung und beim operativen Betrieb auftreten werden aufgezeigt und Handlungsempfehlungen entwickelt, um diese zu bewältigen. Da Bewertungskriterien für die lang-, mittel- und kurzfristigen Planungsprobleme der reihen-

folgestabilen Variantenfließfertigung voneinander abweichen, wird abschließend ein Rahmen für die Zuordnung von Kennzahlen zu Entscheidungsebenen entwickelt.

## Beitrag 2

### *Shared buffer in stabilized automotive production systems*

(Müller, Mareike and Kuhn, Heinrich, 2020)

Automobilhersteller benötigen Strategien, um bei zunehmender Komplexität, dynamischen Rahmenbedingungen und hohem Kostendruck die Stabilität ihres Produktionsprozesses zu gewährleisten. Die konsequente Umsetzung einer reihenfolgestabilen Variantenfließfertigung verkürzt die Auftragsdurchlaufzeiten, reduziert die Handlingkosten und ermöglicht es, den Variantengrad der Produktion kostengünstig zu erhöhen. Ein verwendetes Konzept zur Sicherstellung der Stabilität ist die Einrichtung vollautomatischer Puffer mit wahlfreiem Zugriff, um Staueffekte zu vermeiden und Verwirbelungseffekte auszugleichen. Diese Puffer werden zwischen den Gewerken Karosseriebau/ Lackiererei, sowie Lackiererei/ Montage platziert. Sie generieren hohe Investitionskosten und binden die begrenzte produktionsnahe Fläche.

Der vorliegende Beitrag „Shared buffer in stabilized automotive production systems“ beschäftigt sich mit der Fragestellung, ob ein flexibler zentralisierter Puffer alle Anforderungen einer reihenfolgestabilen Produktion abdeckt und ob er den Gesamtbedarf der Pufferkapazität reduziert. Um die ausgleichende Wirkung eines zentralen Puffers auf das langfristige Stabilitätsniveau von Fertigungssystemen zu quantifizieren, müssen alle implizierten Funktionen von Puffern berücksichtigt werden. Analytische Modelle konzentrieren sich oft auf bestimmte Funktionen und erfordern restriktive Annahmen. Das entwickelte diskrete ereignisbasierte Simulationsmodell ermöglicht eine transparente Analyse und Bewertung der Einbindung eines zentralen Karosseriebau-Speichers in die Materialflusssteuerungen. Zur Überprüfung der Anwendbarkeit und Leistung dieser Methode wird eine empirische Studie mit Daten eines deutschen Automobilherstellers im Premiumsegment durchgeführt. Bei einem Pufferfüllstand mit lackierten Karosserien in der Menge von zwei Dritteln der Tagesausbringung wird ein konstantes Stabilitätsniveau von 98 % oder mehr erreicht. Die Pufferung unlackierter Karosserien zum Ausgleich der Verwirbelungen nach dem Karosseriebau erzielt keinen zusätzlichen Stabilitätszuwachs. Die Ergebnisse belegen die Vorteile der Ausgleichseffekte eines zentralen Puffers mit wahlfreiem Zugriff. In der Studie wird im Vergleich zu einer traditionellen Au-

tomobilproduktion mit zwei getrennten Puffern die erforderliche Pufferkapazität um mehr als 10 Prozent reduziert. Neben der Allokation der benötigten Pufferkapazitäten wurde mithilfe der Fabriksimulation auch ein Steuerungskonzept zur Einbindung des zentralen Puffers in den Produktionsfluss entwickelt und analysiert. Die automatisierte Steuerungslogik greift, insbesondere auch bei auftretenden Störungen, regulierend in den Kreislauf ein.

### Beitrag 3

#### *Assembly line feeding concepts and supermarket allocation in automotive production*

(Lehmann et al., 2020)

Der aktuelle Trend zu einer größeren Modell- und Variantenvielfalt führt zur Entwicklung flexiblerer Produktionslayouts in der Automobilindustrie. Dadurch steigt der logistische Aufwand im Materialfluss. Für eine effiziente Teileversorgung bedarf es einer Anpassung der Inhouse Logistikkonzepte. Um die Montagebereiche weiterhin effizient mit JIS-Teilen zu versorgen, werden so genannte Supermärkte eingerichtet. Supermärkte im Kontext der Automobilfertigung sind dezentrale Logistikbereiche in der Nähe der Montagelinie, aus denen kurz vor ihrem Verbau die benötigten Teile kommissioniert und an das Montageband transportiert werden. Eine wesentliche Planungsaufgabe hierbei ist die effiziente Zuordnung der Teile zu den Logistikbereichen und die Integration dieser Bereiche innerhalb des Produktionslayouts. Da der Platz in der Fertigung knapp ist und viele potentielle Logistikflächen für Montageumfänge reserviert sind, ist das Ziel, die Teileumfänge möglichst ressourcenschonend und Kosten minimierend auf die Supermärkte aufzuteilen. Ein zusätzlicher Kostenfaktor bildet dabei der Transport der Teile vom Supermarkt bis zum Verbauort an der Fertigungslinie. Darüber hinaus müssen materialspezifische Annahmen und Planungsprämissen, wie zum Beispiel die fixe Zuordnung von Teilen zu speziellen Supermärkten oder die Versorgung mehrerer Montagelinien durch einen Supermarkt, eingehalten werden.

Der Beitrag „Assembly line feeding concepts and supermarket allocation in automotive production“ greift das Standortplanungsproblem von Supermärkten in der automobilen Variantenfließfertigung mit mehreren Montagelinien und den genannten Planungsprämissen auf. Es wird ein mathematisches Modell in Form einer gemischt-ganzzahligen Optimierung entwickelt. Die Anwendung des Modells in einer Fallstudie mit einem Datensatz eines deutschen

Premium-Automobilherstellers zeigt, dass mit dem Modell ein Kosten Einsparpotential von 19 Prozent erreicht werden kann. Abschließend werden verschiedene Möglichkeiten aufgezeigt, im Forschungszweig der JIS-Supermärkte weitere Fortschritte zu erzielen.

#### **Beitrag 4**

##### ***Management of buffer systems in automotive stabilized production networks - a qualitative analysis***

(Müller, Mareike, 2020)

Unbeständige Rahmenbedingungen im globalen Wettbewerb, restriktive lokale Marktregulierungen, Innovationssprünge im digitalen Bereich und die steigende Nachfrage nach kundenindividuellen Fahrzeugen erhöht sowohl die Unsicherheit in der Produktnachfrage, als auch die Komplexität der Logistik in Produktionsnetzwerken. Die reihenfolgestabile Variantenfließfertigung ist eine vielversprechende Methode, um sich diesen Zukunftstrends und Unsicherheiten zu stellen. In Produktionsnetzwerken werden Puffer benötigt, um eine langfristige Reihenfolgestabilität zu gewährleisten. Die Allokation der Produktionsressourcen muss in einem integrierten und netzwerkübergreifenden Ansatz erfolgen. Insbesondere die Zuteilung von Pufferplätzen erfordert eine ganzheitliche Planung, da diese sonst einen gegenteiligen Einfluss auf die Leistung des Fertigungsverbundes haben. Ungünstige strukturelle Bedingungen, das Fehlen eines ganzheitlichen Optimierungsansatzes und Zielkonflikte erschweren integrative Lösungsansätze. Lokale Optimierungen und unkoordinierte Versorgungsstrategien senken die Effizienz, reduzieren die Flexibilität und erhöhen die Komplexität von Produktionsnetzwerken.

Der Beitrag „Management of buffer systems in automotive stabilized production networks - a qualitative analysis“ beschäftigt sich mit der Fragestellung, wie reihenfolgestabile Produktionssysteme in komplexe Produktionsnetzwerke nachhaltig implementiert und erfolgreich gesteuert werden. Die in der strategischen Planung auftretenden Zielkonflikte werden analysiert und strukturiert. Bei der Umsetzung einer reihenfolgestabilen Produktion entstehen Zielkonflikte, die auf der Einhaltung der Ausbringung und der Sicherstellung der Reihenfolgestabilität, sowie zwischen den lokalen Optimierungen von Gewerken und den übergreifenden Interessen des Netzwerks bestehen. Abschließend zeigt dieser Beitrag weitere Forschungsmöglichkeiten im Bereich der stabilisierten Variantenfließfertigung auf.

## *Fazit*

Die vorliegende Dissertation analysiert die reihenfolgestabile Variantenfließfertigung im automobilen Umfeld und entwickelt neue Ansätze zur Stabilisierung der Produktion. Um die Planung, Implementierung und Steuerung von reihenfolgestabilen Systemen zu unterstützen, werden Kennzahlen entwickelt (Beitrag 1), mittels objektorientierter Simulation ein Konzept zur Allokation eines zentralen Puffers aufgezeigt (Beitrag 2) und ein Standortplanungsproblem für JIS-Supermärkte gelöst (Beitrag 3). Weiterhin werden Zielkonflikte analysiert und strukturiert, die bei der Implementierung von reihenfolgestabilen Produktionssystemen in komplexen Produktionsnetzwerken auftreten (Beitrag 4).



## Darstellung Eigenanteil

### Nachweis über die von der Doktorandin erbrachten Anteile an den Beiträgen

	Autor(en) und Jahr	Titel	Anteil
1	Müller, Mareike, Lehmann, Marcel und Kuhn, Heinrich (2020)	Measuring sequence stability in automotive production lines	60
2	Müller, Mareike und Kuhn, Heinrich (2020)	Shared buffer in stabilized automotive production systems	90
3	Lehmann, Marcel, Müller, Mareike und Kuhn, Heinrich (2020)	Assembly line feeding concepts and supermarket allocation in automotive production	30
4	Müller, Mareike (2020)	Management of buffer systems in automotive stabilized production networks - a qualitative analysis	100

# Measuring sequence stability in automotive production lines

Mareike Müller, Marcel Lehmann, Heinrich Kuhn

---

## Abstract

We consider the question of how stability in automotive manufacturing systems should be analyzed. This topic is motivated by the need of original equipment manufacturers to evaluate the performance of their production system to ensure efficiency and long-term competitiveness. In order to deal with the increasing complexity of the manufacturing process, original equipment manufacturers need to focus on efficiency in the manufacturing process and supply chain. Since stability is one determining factor of efficiency they need to implement indicators to quantify and visualize stability. While the overall target for the long-, mid- and short-term planning processes remain the same, the application of and specifications for performance measures differ. We present, analyze and evaluate different indicators and reveal their capability to represent the status of stabilized production facilities. We also describe the challenges that arise when implementing these performance measures in real-world production facilities and give recommendations on how to manage these challenges. We provide a framework to assign indicators to planning problems. The transparency provided by accurately chosen indicators fosters understanding of the overall performance of the system and enhances the management of stabilized production.

*Keywords:* Performance Measures, Automotive Industry, Stabilized Production System, Flow Lines, Mixed-Model Assembly Lines, Operational Feedback

---

## 1. Introduction

Recent developments in technology and societal awareness are bringing about great change in the automotive industry, especially in terms of its products, as future cars will tend to be electrified, more connected and capable of autonomous driving (Kuhnert et al., 2018). The ongoing tendency of increasing variants of combustion engine-based models is currently being extended by additional power train platforms such as hybrids, battery electric vehicles, hydrogen fuel cell vehicles and their respective variants. In the present stage of transition where it is unclear which technology approach will succeed or whether there will be a new, more heterogeneous product landscape in the car market, rigidity is not an option. The quantity of different products but also the uncertain demand structure for the different categories of vehicle requires increased flexibility in terms of manufacturing. The resulting lack of planning reliability caused by this uncertainty is dramatically increasing the complexity of manufacturing. Additionally, these new technologies demand substantial investments to enable existing production plants to adjust to new manufacturing procedures. The industry will have to find ways of compensating for falling margins and rising investment throughout this transition. One of the most promising levers for original equipment manufacturers (OEMs) is implementing flexible production systems to cope with the new product variance (Michalos et al., 2010). They ensure company's sales and revenue by continuously adapting their value creation process to new demand structures. Part of this adaptation is tight collaboration between former competitors and the inclusion of companies from different industries and segments into the production networks. These trends are redesigning the value creation network of both, premium and high-volume manufacturers (Göpfert et al., 2017).

The mixed-model assembly line (MMAL) is likely to remain the favorite choice for facing the challenges of the changing manufacturing and market environment in automotive production (Boysen et al., 2015; Zeltzer et al., 2016; Hottenrott and Grunow, 2019). In recent years this production and assembly concept is being enhanced by the integration of automated guided vehicle systems (AGVs), for example (Ilić, 1994; Das and Pasan, 2016). Nowadays, AGV are not only used to supply the assembly line with parts and subassemblies, but also to transport car bodies between the production stations, further increasing the manufacturing flexibility of the entire production system as a result (Kern et al., 2017).

The order sequence continues to be a major aspect within this assembly concept, which

considers the main short-term objectives of all production stages as well as the supply chain. The order sequence is usually determined several days before the start of the production. The material requirement forecast that derives from this preferably unchanged initial sequence enables a lean material flow with increased just-in-sequence (JIS) delivery. This approach is highly favourable for the manufacturing of products that are full of variety. The underlying production concept, which is based on an unaltered assembly sequence is known by several terms such as in-line vehicle sequencing (ILVS) (Inman, 2003), pearl necklace concept (PNC) (Meyr, 2004; Meissner, 2010; Boysen et al., 2012), pearl chain concept (PCC) (Weyer and Spath, 2009; Wagner and Silveira-Camargos, 2012) or stabilized production system (SPS) (Lehmann and Kuhn, 2019), and is practiced by many automotive manufacturers around the world. The pearl necklace/chain symbolizes the production flow of orders (pearls) that are aligned in a fixed sequence (chain). Within the present study we denote this production concept using the more general term stabilized production system. In real-world application the initial sequence is scrambled throughout the production process due to varying lead times, machine breakdown, quality issues or material shortages. This results in additional logistical effort, since the JIS material flow has to be adapted accordingly, which requires storage space and handling operations (Lehmann and Kuhn, 2019; Müller and Kuhn, 2020). The intensity of scrambling is therefore directly linked to the logistical effort, or in other words the economic performance of the production site. The stability of the production sequence is hence the critical success factor for an SPS, so it needs to be carefully measured and controlled.

Implementing and operating an SPS therefore requires adequate performance measures (PMs) to control and steer the entire production system in accordance with the respective SPS's objectives. The literature, however, lacks comprehensive and in-depth analyses of those PMs to evaluate the stability level of complete production systems or individual production stages. This paper aims to overcome this gap and contributes to the literature as it presents the most important stability measures and compares them with one another with regard to relevant stability objectives. Furthermore, it analyzes their applicability using real world production data. It also reveals potential obstacles when implementing these measures in automotive production systems. The obstacles are discussed and several recommendations for implementing PMs in the automotive industry are derived from the insights.

The paper is structured as follows. Section 2 briefly introduces the characteristics of

automotive production systems and describes the approach of stabilized production. Furthermore, it provides a brief overview of general PMs in the automotive industry and discusses the explanatory power of these indicators in terms of describing stability. In Section 3, the terms sequence scrambling and stability are explained in depth and put into the perspective of the production flow. Section 4 introduces six stability-oriented performance figures that are compared and evaluated based on several scrambling scenarios. Section 5 displays the application to real-world production data and managerial insights. Section 6 concludes the article with a summary and an outlook on further research.

## **2. Production systems in the automotive industry**

### *2.1. Automotive production*

A fully assigned automotive manufacturing site consists of four production steps: sheet metal shop, body shop, paint shop and final assembly line. These production steps are sequentially organized and physically connected by conveyor and buffer systems. Various types of car and body style are mainly assembled in a conjoined manner within one production site since the order of the production steps are generally identical for all cars. While the lead time of different models in the body and paint shop vary, they are all the same at the final assembly line (Boysen et al., 2008). However, some cars need more assembly time because they require more parts installation. Work-intensive orders are followed by orders with less work-intensive features to balance the overall workload. This approach is embedded in the creation of the initial sequence. The resulting leveled workload allows the application of identical takt time for the entire mix of models produced on the same assembly line.

OEMs outsource the majority of parts and components to suppliers due to the high number of different components required at the assembly line. These suppliers contribute up to 70 percent to the value added of an entire automobile. The structural design and management of the supply chain is therefore the key success factor of automobile production networks (Gehr and Hellingrath, 2007). Despite all the possible sourcing strategies, most of the parts delivered are installed at the final assembly, which is therefore the center of these complex networks, since the material flow and car body flow are brought together. The increasing variety fosters the ongoing trend of outsourcing parts and components to suppliers. The diminishing number of parts manufactured in house and the rising number of components supplied to the

assembly lines results in a growing number of parts moving inside the internal and external logistics networks. The orientation towards JIT and JIS delivery and the resulting reduction of undesirable safety stocks in combination with the wide-spread supplier networks and the unpredictable demand of the assembly pushes the capacity of production facilities to its limits. These conditions have led to a new orientation towards lean manufacturing aspects along the automotive supply chain (Gusikhin et al., 2007).

## *2.2. Stabilized production*

As recent decades have shown, the production system and supply strategies are in constantly ongoing evolution. Studies in literature describe this continuous improvement, whether the development of JIT production (Savsar and Al-Jawini, 1995), the emphasis on excellence in supply management (Shin, 2000), the transition from built-to-stock to built-to-order production (Meyr, 2004), or the progress to highly flexible MMAL concepts (Boysen et al., 2015). Another aspect covered is a production system with a stable order sequence (Meissner, 2010) and JIS supply networks with tightly coupled buyer-supplier relationships (Wagner and Silveira-Camargos, 2012). All these concepts combined lead to a system that can be described as an SPS. Many German OEMs such as BMW (Rumpelt, 2009), AUDI (Rumpelt, 2010; Beuthner, 2018), Porsche (Fecht, 2011) and Daimler (Standl, 2016) have already implemented this concept and continuously enhanced it (Müller and Burges, 2020). The key point of stabilized production is an unaltered assembly line sequence that is guided into a fixed production sequence several days before the beginning of the manufacturing process. SPSs enable OEMs to receive parts and subassemblies in exactly the same order by communicating the fixed production sequence to the internal and external suppliers a few days prior to assembly (Grinninger and Meißner, 2006).

*Advantages of stabilized production.* One of the main benefits is establishing JIS logistics strategies to reduce operational costs by scaling down the floor space and labor required at the final assembly line. Besides saving expenses, OEMs down size space for logistical operations at the production site and can use the areas gained to adapt their assembly. In their study on managing risks in JIS networks, Wagner and Silveira-Camargos (2012) conclude that sequence stability and implementing an SPS is the recipe for success of JIS logistics strategies. Furthermore, the overall product and process quality at stabilized production sites increases as transparency within the production process is high and the chances of assembling an incorrect

part diminish (Inman, 2003). The enhancement of transparency can be attributed to the fact that any problem in the production process causes scrambling which is easily detected. Within the aforementioned studies SPSs seem primarily to be motivated by the needs of the production, logistics and sourcing departments. Nevertheless, in practice the objectives are multifaceted and heterogeneous, as all corporate units profit from sequence stability. The marketing and sales unit benefit from adjusting demand planning at short notice, scaling up the model mix and attaining the completion date of the order. The research and development department also gain an advantage, as new vehicle models can be integrated into production at an earlier stage. Operational control can keep track of supplier performance and material requirements. Another benefit of the concept is that it supports complex supply networks. In these networks with multiple interdependent actors the stabilized production philosophy causes more efficiency as instability directly affects all other participants and leads to even more instability. In addition, the initial sequence considers the objectives and restrictions of all production steps of the OEM. E.g., at the final assembly, car sequencing rules are applied to meet a balanced workload, minimize set-up costs and level out demand. Therefore aiming for a high stability level means preserving these objectives.

*Requirements of stabilized production.* Implementing stabilized production requires a diverse set of accompanying measures otherwise the above-mentioned advantages cannot be realized. These adaptations include changes to the organizational structure around the production process, adaptations to the production process itself and, if technically necessary, hardware installations concerning the production resources. Both are linked to expenditure either in terms of operating or investment costs. In many cases the buffer system for the car bodies needs to be adapted to the requirements of the SPS. The buffers have to cover an additional function, i.e., restoration, and therefore capacity, especially at the front of the final assembly line, has to be increased. In addition to the increased volume, random access for most buffers is required to re-sequence efficiently. On the process side, the quality level of the manufacturing process has to be increased to avoid scrambling caused by the additional time required by rework operations. Additionally, rework needs to be reorganized such that it can be performed immediately at the end of the production step or even during the process. Usually, orders with missing parts are blocked in front of the final assembly line to avoid rework. In SPS it is common to allow certain orders with missing materials to enter final

assembly if the missing parts can be installed afterwards with reasonable effort. This reduces the scrambling but the required processes need to be established. As a result, the rework area (after the final assembly) needs to be adapted in terms of capacity. Of course suppliers need to provide a certain stability as well since disruption on the material side could force the final assembly to stop at very short notice. Therefore, a high and constant level of product quality and reliable delivery schedules are required. To ensure these two aspects a certain degree of transparency is required, which is usually based on a rapid and reliable exchange of information. Investments thus need to be made in certification and technology so that information and tracking status can be shared. Specific key performance indicators (KPIs) are required to be aware of the current stability situation of the production system to be able to derive adequate measures if necessary. As noted by Wagner and Silveira-Camargos (2012) a key issue for attaining process transparency as well as managing the supplier network effectively is to establish PMs that track sequence stability.

### *2.3. Performance measures*

In the remainder of this section we will briefly describe the common KPI categories of the automotive production environment and make some remarks concerning their suitability for stability measurement.

*Throughput.* Throughput-oriented measures are commonly used to determine the performance and efficiency of assembly lines. They measure the average number of parts produced by the last machine in the production system within a shift, day, week or any other unit of time (Li et al., 2009).

*Work-in-process.* Another important category are the work-in-process (WIP) indicators, which are inventory-oriented measures. WIP includes all car bodies that are currently within the production process. Production management aims to minimize the lead time and WIP, as it requires storage space, causes tied capital and reduces the flexibility to adjust production volume at short notice (Papadopoulos and Vidalis, 2001).

*Lead time.* Time-oriented measures evaluate the production process on meeting the target schedule. The overall lead time of an order, as a prominent example, is the period from the beginning of the production process in the body shop to delivery to the distribution center. This includes processing-, queuing- and transportation-time. One very important



measure in automotive production is the lead time required to complete a single task. It is called takt time, and the configuration of assembly shops is usually based on this figure. Another group of indicators are non-productive time related, and measure when production machines or units fail to perform. They consist of idle time, setup time and the mean time to repair (MTTR). The MTTR represents the average time required to fix a failed component or machine. Reducing the MTTR decreases the downtime as well as the lead time. Tracking and reducing the lead time, WIP, takt time, downtime and MTTR helps to identify bottlenecks in the production process and is considered one of the most essential goals of continuous improvement (Li, 2013).

*Meeting customer due dates.* Another important class are the customer-oriented measures in production, which commonly aim at delivery performance. Measuring delivery performance includes figures like total-days-late, average-days-late, number-days-late-of-latest-item, on-time-delivery and customer service level. These PMs display whether an order has been delivered on time (Lovgren and Racer, 2000).

*Quality.* Quality is defined as an order that meets customer needs, is free from defects and in accordance with the expected quality level (Juran, 1999). To ensure this quality metrics are inevitable. The PM system yield is the ratio of the number of non-defective parts produced against the total output of the system (Colledani and Tolio, 2011). Quality inspections are used to check and reject defective car bodies or parts within the production process. The rejection rate displays the number of defective items compared to the total number of parts inspected. High quality of the WIP and finished goods reduces rework hours, material waste and the average lead time (Han and Park, 2002). The first-, second-, and third-run quota is a PM used to count rework cycles in automotive production lines (Li et al., 2008). Characteristically in the paint shop a high number of car bodies receive rework at the spot repair or run through the manufacturing step of applying the top coat a second time (Dössel, 2008).

*Evaluation of classical KPIs.* As mentioned previously, the production sequence is still a crucial factor in automotive production. Several of the above-mentioned ambitions are therefore embedded as objectives in the planning process of the sequence. The batch size in the paint shop is one of these objectives for example. Batches are scheduled to avoid set-up times

and minimize mean lead time (Feng et al., 2012). Undoubtedly the four categories of KPIs described are connected with stability and therefore they give some insight into the stability. For example a reduced WIP inside the restoration buffer can indicate a low stability level. The same holds true for a high second- or third-run quota, heavily varying lead times and downtime in parallel structures. But besides giving hints, which may not be correct in every situation, they do not give a clear statement on the stability level itself. Specific stability measures are therefore required. Another positive effect of stability measures is that all other sequence-related criteria that have been considered within the planning of the initial sequence are observed simultaneously. Every possible metric for penalizing deviations is conceivable for measuring the target. It should be noted in this regard that the minimization of deviations between actual and target production schedules is an approximate objective for the underlying costs (Boysen et al., 2009).

*Stability measures.* Stability measures quantify the change of an order sequence compared to a reference sequence and are clearly part of the sequence-oriented category. Even though they are crucial for the successful application of SPSs, less attention has been paid to these indicators in literature compared to the other types of indicators (Amrina and Yusof, 2011). As a result, several gaps exist that this paper will strive to close. A review of the literature reveals that stability measures are often not clearly specified or referenced and there exists no consistent notation. They are described in slightly different variations (Weyer and Spath, 2001; Weyer, 2002; Inman, 2003; Meissner, 2010; Günther, 2017; Lehmann and Kuhn, 2019). Meissner (2009) concludes that the PM sequence deviation meets all requirements for the evaluation of sequence stability and is directly suitable for controlling SPS. The results were cited in further papers (Grinninger, 2012; Cedillo-Campos et al., 2017). In the paper of Lehmann and Kuhn (2019) several indicators are presented and one key figure is chosen to measure stability. Interviews with automotive practitioners reveal that often a single key figure is used but does not cover all aspects of an SPS. Among others, Günther (2017) describes this key figure. Weyer and Spath (2001) and Weyer (2002) introduce a similar key figure as used in practice. We show that PMs on sequence stability introduced in literature are not sufficient to evaluate SPSs at full range. A best practice is needed to compare, classify and evaluate SPS-related performance figures. Moreover, different measures need to be taken into account that consider the long-, mid- and short-term decision-making process of SPSs.

Furthermore, the paper at hand contributes to the literature as it analyzes the applicability of KPIs to real-world production data. It reveals potential obstacles when implementing indicators in automotive production systems and provides recommendations concerning the application of KPIs.

### **3. Sequence stability as a performance indicator for production lines**

Designing and implementing effective PMs in SPSs requires a profound understanding of the relationship between sequence scrambling, lead-time distribution and operational processes. The following section provides a detailed explanation of this relationship. Scrambling describes the change of order sequence during the production process (Inman, 2003). Orders fall behind or pull ahead in the sequence when they leave the linear production flow and enter process steps that are additional or organized in parallel and vary in their lead time. These lead-time variations can be categorized into intentional and unintentional lead-time extensions.

#### *3.1. Intentional lead-time extension*

Basically, there are two aspects that lead to intentional scrambling of the initial sequence before reaching the final assembly line. Production-induced varying lead times for different body styles are the first cause for scrambling. For example, convertibles require additional production steps in the body shop and are therefore inevitably bound to need a longer lead time compared to the standard model. This is also the case in the paint shop where the time to apply high-gloss piano lacquer differs greatly compared to the lead time of a standard top coat. Depending on the production network these steps can also be performed by suppliers outside the plant and require a significantly increased additional lead time.

The second reason for intentional scrambling is driven by the application of various car sequencing rules and quotas during the production process. The different production steps usually do not share the same optimal sequence, which raises the necessity of rearranging the sequence of jobs before entering the subsequent production segment (Lahmar et al., 2003). For example, while the paint shop benefits from blocks of the same color, since they cause fewer cleaning procedures, the remaining production steps do not benefit from this specific requirement. Another type of sequencing rule is used to reduce work overload by avoiding the concentrated occurrence of specific car features in the production sequence. This means the

occurrence of cars with work-intensive operations, e.g., installation of the sunroof at the final assembly, is limited within the sequence. If this rule is in place then there has to be a certain number of cars without a sunroof between two cars featuring that attribute. These rules are usually related to the final assembly line but are already applied in the initial sequence. Since intentional and unintentional scrambling changes the sequence, these rules are not fulfilled when the order arrives at the final assembly. This means strict application of these rules at the front of the final assembly requires additional re-positioning of the orders. A sequence that has already been scrambled is likely to be disturbed even more as a result. This is especially the case if the number of rules applied and the number of cars bound to such a rule are high.

Buffers located between the body shop and paint shop and especially between the paint shop and final assembly line are used to enable these intentional scrambling operations such as batching of colors or enacting of sequencing rules. They are required to transfer the sequence initially planned into subsequent sequences and to restore the sequence.

One approach that reduces the effect of intentional scrambling is to modify the release dates of the orders according to their expected lead times. This means there is additional time added for some cars at specific production steps compared to the standard lead time. The extra time is used during production and the orders finish at the desired position. This approach considerably reduces the number of buffer places for re-sequencing (Inman and Gonsalvez, 1997). The approach is especially applicable to level unequal production lead times known in advance, such as quality control.

### *3.2. Unintentional lead-time extension*

Unintentional scrambling is often caused by defects related to the car body. There exist different handling strategies depending on the type of flow line. One concept is to mark the defective car and redirect it into repair loops or off-line repair stations. While these cars are reworked, all other car bodies continue the regular production process and overtake the defective order, which results in a change of sequence. So-called line-stop or zero-defect strategies are an alternative approach to prevent these scrambling effects. These strategies cause the assembly line to stop until the defective car is repaired (Robinson et al., 1990). This reduces the production volume remarkably since the process for all cars in production is stopped with every line stoppage. This practice is therefore rarely applied. Unintentional lead-time extensions usually vary in time, since they depend directly on the time required to solve

the quality problem at hand. The most difficult kind of quality-induced lead-time extensions occur when the car body has to be re-assembled from scratch. In this case replenishment time is at least as long as the production lead time plus, if necessary, the time to reorder the parts required.

Another source of unintentional scrambling is random downtime of specific model-induced machines. For example, convertibles require different operations compared to the standard model in the body shop. These operations are often processed on separate flow lines. These so-called y-shaped production flow lines often lack a corresponding decoupling buffer. This means there are two parallel product flow lines that merge directly into one sequence. If one of these assembly line stops producing while the other continues, the resulting sequence scrambles due to the missing orders that were originally anticipated in the merged sequence. Besides these production process related reasons for scrambling, there are external factors, e.g., supplier shortage. Missing material, such as customer-individualized lacquer, has the potential to block an order for quite a long time.

### *3.3. Visualization of sequence stability*

Intentional and unintentional lead-time extensions interfere with the assumed fixed lead time of an order. Figure 1 schematically displays the lead time distribution and corresponding scrambling profile. The graph on the left shows an example of a typical lead-time distribution. All values are above zero and above a certain threshold, which corresponds to the minimal lead time. The minimal lead time equals the pure processing time of an order with the least work-intense or time-consuming production steps. The lead times realised are generally longer than the minimal lead time. These extended times result from longer or additional processes, varying occupancy of buffers within the production system, downtime and rework. These circumstances cause the typical right-skewed distribution. The majority of the vehicles feature a lead time that is slightly less than the average lead time. Some orders feature a longer lead time or additional rework time and cause the tail on the right-hand side of the distribution. The distribution declines slowly on the right since there are only a few cars with extremely long lead times, often caused by missing parts.

The varying lead times of the car bodies result in orders being overtaken and therefore in a change in position compared to the original sequence. This change is schematically displayed on the right-hand side of Figure 1. Some orders are therefore in a position that is ahead

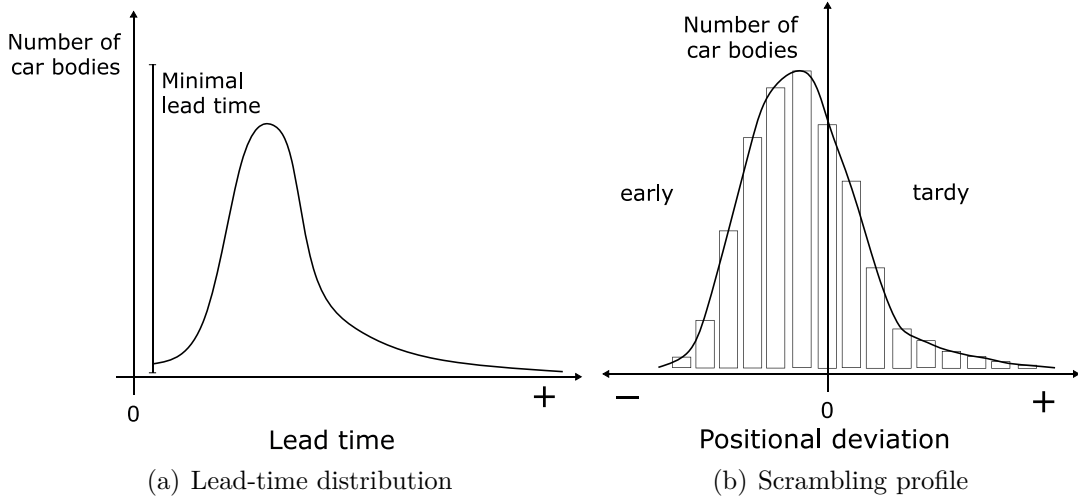


Figure 1: Distribution of lead time (on the left) and the distribution of lateness, i.e., earliness and tardiness (on the right)

of the position originally scheduled (early), while others fall behind (tardy). The positional deviation is calculated by subtracting the incoming position number of an order from its outgoing position number.

This results in a negative value (early), a positive value (tardy) or a zero (no positional change). The plot is basically a histogram with a container of size one, where the frequency of the ascending deviations is plotted. A more detailed explanation is given in Section 4.1. A real-world example is shown and explained in the next paragraph. An SPS requires a narrow scrambling profile, meaning as many deviations as possible should be close to zero. These kinds of profile can be restored with less buffer capacity than wider profiles.

### 3.4. Sequence stability in the production flow

The characteristics of intentional and unintentional lead-time extensions differ significantly along the car body flow (CBF) as they occur for different reasons. Shop-specific patterns in the distribution of scrambling are revealed when observing the production segments individually. Figure 2 displays this effect on the sequence stability in the course of the production flow based on real-world data recorded from an OEM in the premium segment. The calculations are performed as described in the previous section, where the position from the incoming sequence is recorded at the beginning of each shop and the position number of the outgoing sequence is registered after the completion of the respective production segment.

We follow the CBF as introduced in Section 2 and explain reasons for different appearances. The fusion welding of the body shop is a highly automated flow line and products move

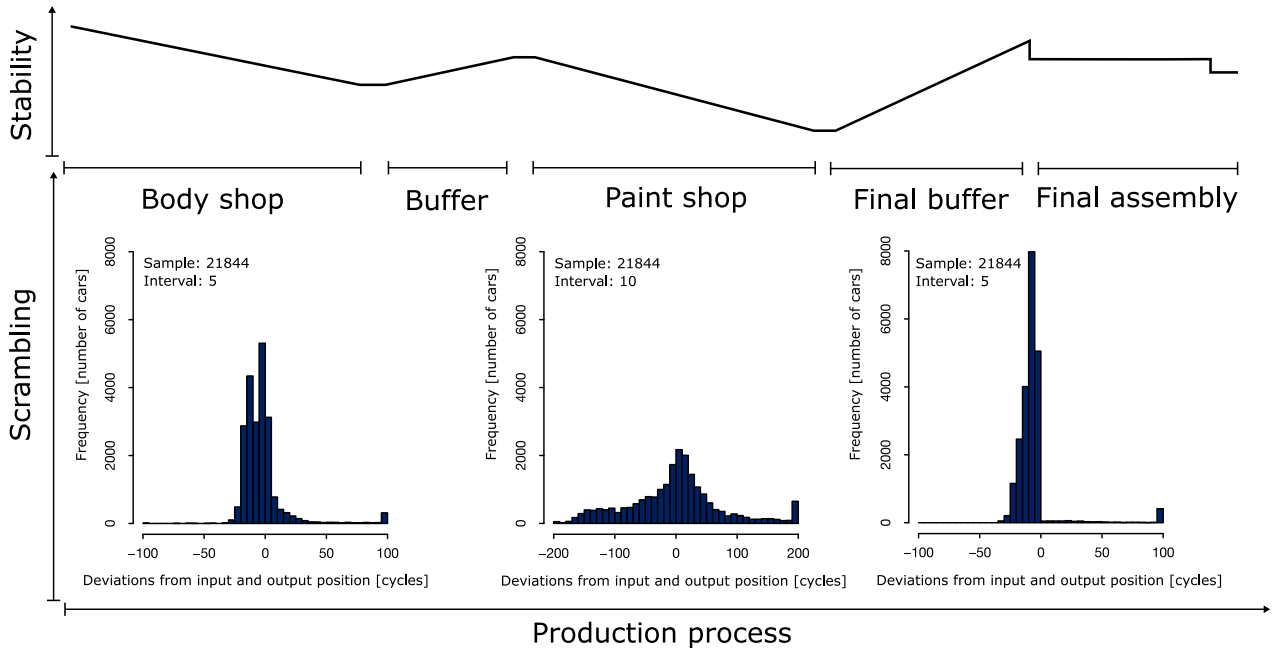


Figure 2: Scrambling in the car body flow

sequentially from one work station to another. Hence, scrambling is not expected. However, flow lines have a dynamic behavior due to machine breakdown, variations in process times and blocking of machines (Gershwin and Schick, 1983). While machine breakdowns or blocking in a single line assembly have no effect on the production sequence, different part routing, e.g. convertible cars, scrambles the sequence. Since this is a physical process there are randomly occurring deviations that require inspection or rework for some cars, resulting in extended lead time. Figure 2 (left-hand side) shows the distribution, which leads to a drop in sequence stability during operations in the body shop. The buffer in-between the body and the paint shop is used to restore the sequence. However, this is only possible up to a certain level. The sequence entering the paint shop therefore no longer matches the initial sequence.

There are several reasons for the typical shape of the distribution of the paint shop (center of Figure 2). In the best scenario, the car body runs through the process of applying the top coat once, passing the spot repair stations and immediately exiting the paint shop. Those orders cause the shape of the left-hand side of the distribution. Varying lead times between color options are one reason for the spread of the distribution. The largest effect on distribution is caused by rework, including spot repair and reruns. At the end of the paint shop the surface is inspected carefully. About 50 percent of cars are moved to a spot repair cabin to quickly remove minor defects in the top-coat. An additional 10 percent of

cars have larger defects and need a rerun through the entire top coat production line (Dössel, 2008). This effect pushes the distribution to the right. These patterns can also be found in literature (Inman, 2003; Fournier and Agard, 2007). The sequence leaves the paint shop with a significantly lower stability level. The final buffer arranges orders aligned to the sequence initially planned by sorting them according to their ascending sequence number. Since scrambling inside the paint shop is the strongest, the buffer size is considerably larger compared to the one after the body shop in order to be able to restore the sequence. Nevertheless, the re-sequencing volume is limited to an economically reasonable level and therefore not able to restore every last order of the sequence. The higher the volume in the final buffer, the higher the system time for the re-sequencing process. The sequence stability therefore improves with the increasing lead time in the final buffer. The remaining instant drop in stability at the entrance to the final assembly is due to blocked orders or the enforcement of sequencing rules. Both activities reveal their impact at the moment the final sequence is dispatched. There is a trade-off between strictly meeting all sequencing rules and the stability level. If all sequencing rules are applied this can reduce the sequence stability level additionally. This means, the dispatching strategy is based on sequencing rules and only the second sorting criteria is the ascending sequence number.

The scrambling profile on the right-hand side of Figure 2 is different to those that precede it. It displays the stability level of the sequence at the moment when it gets dispatched into the final assembly line. The stability level quantifies the sequence dispatched compared to the sequence initially planned. Compared to the other scrambling profiles this one shows the lowest spread because it has already been restored within the final buffer. Once the car body is released into the final assembly line additional scrambling cannot occur since the flow line is strictly arranged and overtaking is technically impossible. In addition, the JIS supply strategy applied strictly limits altering of the sequence released into the assembly line. This sequence defines the provision of the associated parts or components, which are supplied in sequence that is 100 percent identical. Altering this sequence would lead to remarkable logistical problems during the assembly process.

For the sake of completion there is a significant degree of scrambling at the rework area of the final assembly. Since the following operational steps do not depend on a stabilized sequence anymore, the stability is not relevant and therefore not measured in this area.



## 4. Quantifying sequence stability in production lines

Performance measures can be defined as the attempt to quantify the efficiency and effectiveness of an action within a system (Neely and Platts, 2005). In SPSs these indicators should measure adherence to the planned production sequence, since this is the primary goal of such systems (de Toni and Tonchia, 1996). In this context, stability is the polar opposite of instability or scrambling, so both of the latter are valid to analyze SPS. In this section we first define basic scrambling measures, i.e., absolute measures. Afterwards we formulate and analyze six relative stability indicators using a consistent notation. The KPIs are displayed and evaluated based on diverse scrambling scenarios to gain a better understanding of their properties.

### 4.1. Basic and absolute scrambling measures

In order to measure sequence scrambling adequately, each customer order  $c$ ,  $c \in \{1, 2, \dots, C\}$  needs to be associated with a sequence number, denoted as  $SN_c^x$  with  $SN_c^x \in \{1, \dots, N\}$ , referring to their position in the sequence at a specific step (location) in the production process, i.e.,  $x$ ,  $x \in \{0, 1, \dots, P\}$ , respectively. The bigger the  $x$ , the later this location is positioned within the production process. In real-world production systems location  $x$  can for example be the exit of the body shop, the exit of the paint shop, or the entrance of the assembly line. In the automotive industry a position, defined as  $SN_c^x$ , is also referred to as production cycle. We assume that each order  $c$  occupies exactly one position or cycle, so there are no empty cycles. This leads to the special case that the total number of sequence numbers equals the total number of orders considered,  $N = C$ . The initial sequence number, which displays the position in the frozen sequence originally planned is referred to as  $SN_c^0$  with  $SN_c^0 = c$ ,  $c \in \{1, 2, \dots, C\}$ . The sequence number and especially the initial sequence number are the fundamental elements for all following calculations. Please note that we generally assume that no customer order  $c$ ,  $c \in \{1, 2, \dots, C\}$  falls below position 1 or jumps ahead of position  $N$ . This means that each order remains within the observation period  $C$  considered.

An order can change its position within its sequence during the production process. Measure  $SD_c^{x,s}$  quantifies this deviation in position.

$$SD_c^{x,s} = SN_c^x - SN_c^s \quad 0 \leq s < x, \quad s, x \in \{0, 1, \dots, P\}, \quad c \in \{1, 2, \dots, C\} \quad (1)$$

The measure quantifies the absolute difference between the sequence number at location  $x$ ,  $SN_c^x$  and the reference sequence number of order  $c$  at location  $s$ ,  $SN_c^s$ . A negative value of  $SD_c^{x,s}$  indicates that order  $c$  has moved ahead. A positive value results if order  $c$  has fallen behind. The measure reflects the amount of scrambling an order has suffered. If the position remains unchanged, the result equals zero. A common use of this figure is to determine the scrambling within a specific production stage. For this kind of determination it is usual not to use one single value of  $SD_c^{x,s}$ , but all values from the observation period  $C$ . This information is usually displayed as an absolute distribution  $D(SD_{\{1\dots C\}}^{x,s}) = \{f(a_1), \dots, f(a_j)\}$ , with  $(a_1, \dots, a_k)$  being the realization of  $SD_c^{x,s}$ ,  $c \in \{1, 2, \dots, C\}$  and  $f(a_j)$  being the frequency of  $a_j$ . The distribution is commonly referred to as a scrambling profile (see Section 3.3).

The figure  $SD_c^{x,s}$  however allows no statement related to an increase or decrease in stability level induced by the production stage being considered. In order to make a statement of this kind, a comparison with the initial sequence number  $SN_c^0$  is required. Variable  $SD_c^{x,s=0}$  denotes this special case where the sequence number is referred to the initial position originally planned (Weyer, 2002; Inman, 2003). We denote this special case  $SD_c^x$ . A negative value of  $SD_c^x$  indicates an early order. A positive value of  $SD_c^x$  indicates a delayed or tardy order. Positive as well as negative values should, if possible, be avoided since this leads to additional operational effort. A value of zero occurs, when an order is exactly at its originally scheduled position. As stated by Inman (2003), the values  $SD_c^{x,s}$  or  $SD_c^x$  add up to zero for the entire number of orders considered,  $C$ .

$$\sum_{c=1}^C SD_c^x = 0 \quad x \in \{1, 2, \dots, P\} \quad (2)$$

Hence, the mean of all values  $SD_c^x$ ,  $c \in \{1, 2, \dots, C\}$  is also zero, and can not be used for evaluation purposes. This is the case since the production process is a closed system, meaning that at each instance when one car enters the system another will leave it. So if one customer order falls behind, this results in a positive  $SD_c^x$  value, but at the same time at least one other order passes, causing a negative  $SD_c^x$  value. A positive  $SD_c^x$  value therefore automatically generates one or several negative  $SD_c^x$  values and vice versa.

It is important to mention that SPSs usually do not allow cars to actively be brought forward. Orders with a negative  $SD_c^x$  value are therefore always caused by cars with a positive  $SD_c^x$  value.  $SD_c^x$  is the simplest way of quantifying sequence scrambling, but also the

basis for more complex calculations that are introduced in the next section. Table 1 presents a simplified example of  $SD_c^{x,s}$  and  $SD_c^x$  values for ten production orders. This example could represent the beginning (location  $s$ ) and the end (location  $x$ ) of the paint shop. Location “0” refers to the sequence initially planned at the beginning of the production line.

Table 1: Quantifying  $SD_c^{x,s}$  and  $SD_c^x$  for an example of ten orders,  $C = 10$ ,  $0 < s < x$

$c$	$SN_c^0$	$SN_c^s$	$SN_c^x$	$SD_c^{x,s}$	$SD_c^x$
1	1	1	2	1	1
2	2	2	1	-1	-1
3	3	4	3	-1	0
4	4	3	5	2	1
5	5	8	6	-2	1
6	6	6	4	-2	-2
7	7	5	9	4	2
8	8	7	7	0	-1
9	9	9	8	-1	-1
10	10	10	10	0	0
Sum	-	-	-	0	0

#### 4.2. Relative stability indicators

We present six relative KPIs quantifying the stability level at a certain location  $x$  of an entire production system. We consider an observation period covering  $C$  customer orders that accordingly covers  $N = C$  production cycles. Note that the number of customer orders  $C$  equals the number of production cycles of the corresponding observation period. All the KPIs selected are measured in relation to the production volume  $C$ , resulting in relative values between zero and one hundred percent. A relative value increases the comparability with other production stages or even other plants, independent of the associated production volume. In addition, this ensures direct comparability between all indicators selected and enables a comparison of different scenarios of production sequences. The indicators are either position-based, where the actual positions of orders are compared to their respective reference positions, or neighborhood-based, where the actual positions of orders are compared to their respective predecessors or successors. Since stability is the direct opposite of scrambling, all indicators are calibrated to measure stability in order to ensure comparability. Table 2 summarizes the notation used to quantify the KPIs selected.

Table 2: Notation

Variable	Description	Definition
$C$	Number of orders within the observation period	$\{1, 2, \dots, c, \dots, C\}$
$P$	Number of steps (locations) of the entire production process	$\{0, 1, 2, \dots, s, \dots, x, \dots, P\}$
$N$	Number of sequence numbers or cycles of the observation period	$\{1, 2, \dots, n, \dots, N\}$
$SN_c^x$	Sequence number of order $c$ at production location $x$ ; $SN_{c=0}^x = 0$	$\{1, 2, \dots, N\}$
$SN_c^0$	Originally scheduled sequence number of order $c$ ; $SN_{c=0}^0 = 0$	$\{1, 2, \dots, N\}$
$SD_c^{x,s}$	Sequence deviation of order $c$ at location $x$ compared to the sequence at location $s$	$SN_c^x - SN_c^s$
$SD_c^x$	Sequence deviation of order $c$ at location $x$ compared to the sequence originally scheduled	$SN_c^x - SN_c^0$
$O_c^x$	Maximum of the original sequence numbers of all orders dispatched before order $c$ at location $x$	$\max_{d \in \{1, 2, \dots, C\}} [SN_d^0 \mid SN_d^x \leq SN_c^x]$
$B_{\max}$	Maximum amount of orders $c$ simultaneously out of position in observation period $C$	$\max_{c \in \{1, 2, \dots, C\}} [O_c^x - SN_c^x]$
$SV_c^{SD_c^x \leq 0}$	Sequence deviation of order $c$ at location $x$ is less than or equal to zero (1), else (0)	$\begin{cases} 1 & SD_c^x \leq 0 \\ 0 & \text{else} \end{cases}$
$SV_c^{SD_c^x \leq z}$	Sequence deviation of order $c$ at location $x$ is less than or equal to $z$ (1), else (0)	$\begin{cases} 1 & SD_c^x \leq z \\ 0 & \text{else} \end{cases}$
$SV_c^{SD_c^x = 0}$	Sequence deviation of order $c$ at location $x$ equals zero (1), else (0)	$\begin{cases} 1 & SD_c^x = 0 \\ 0 & \text{else} \end{cases}$
$SP_c^x$	Predecessor of order $c$ at location $x$ equals the predecessor of the initial sequence (1), else (0)	$\begin{cases} 1 & SN_{c-1}^x + 1 = SN_c^x \\ 0 & \text{else} \end{cases}$
$SP_c^{SD_c^x < 0}$	Predecessor of order $c$ at location $x$ equals the one of the initial sequence and its sequence deviation is less than zero, i.e., order $c$ is earlier than originally scheduled (1), else (0)	$\begin{cases} 1 & SN_{c-1}^x + 1 = SN_c^x \wedge SD_c^x < 0 \\ 0 & \text{else} \end{cases}$

*Alpha stability level.* The alpha stability level,  $SL_\alpha^{[\dots]}$ , belongs to the group of position-based stability indicators. It quantifies the consistency of the actual positions of orders compared to their respective reference positions.

$$SL_\alpha^{[\dots]} = \frac{\sum_{c=1}^C SV_c^{[\dots]}}{C} \quad (3)$$

In general the indicator counts all sequence violations allowed and puts the sum in relation to the total number of orders of the observation period. Several variants of alpha stability level can be defined depending on the magnitude of position deviations that are tolerated and/or which kind of deviations, i.e., positive and/or negative, are considered.

The  $SL_\alpha^{SD_c^x \leq 0}$  considers all undelayed orders.

$$SL_\alpha^{SD_c^x \leq 0} = \frac{\sum_{c=1}^C SV_c^{SD_c^x \leq 0}}{C} \quad x \in \{1, 2, \dots, P\} \quad (4)$$

The indicator counts all orders that are not delayed and sets this number in relation to the total number of orders. This version of alpha stability level is commonly used in the German automotive industry (Günther, 2017).

A second version of alpha stability level,  $SL_\alpha^{SD_c^x \leq z}$ , allows for a certain degree of tardiness. It counts all orders that are delayed less or equal to  $z$  cycles.

$$SL_\alpha^{SD_c^x \leq z} = \frac{\sum_{c=1}^C SV_c^{SD_c^x \leq z}}{C} \quad x \in \{1, 2, \dots, P\} \quad (5)$$

In this case it is assumed that an available buffer can store  $z$  vehicles, which allows up to  $z$  vehicles to be resequenced. The indicator therefore considers orders as “undelayed” that feature a deviation below or equal to a permitted range of  $z$  cycles compared to its original position.

A third version of alpha stability level,  $SL_\alpha^{SD_c^x = 0}$ , only counts those orders that are exactly at their reference position. All  $SD_c^x$  values that equal zero are summed up.

$$SL_\alpha^{SD_c^x = 0} = \frac{\sum_{c=1}^C SV_c^{SD_c^x = 0}}{C} \quad x \in \{1, 2, \dots, P\} \quad (6)$$

The indicator only counts orders that are assembled pin point at their originally planned position. This quantification of the alpha stability level is much more rigorous than the version of Eq. (4) and (5). Both delayed and early orders remain unconsidered.

*Beta stability level.* The beta stability level,  $SL_\beta$ , is a useful indicator for the buffer capacity requirement for car bodies. Besides that, it is an exact measure for determining the average

logistical space required to store the parts that belong to the car bodies delayed. The indicator belongs to the group of position-based indicators. It is for example used in the premium sector of the German automotive industry to measure the stability level at a certain location of the production system (Lehmann and Kuhn, 2019).

$$SL_\beta = 1 - \frac{\sum_{c=1}^C \frac{O_c^x - SN_c^x}{C}}{C} \quad x \in \{1, 2, \dots, P\} \quad (7)$$

The indicator,  $O_c^x$ , quantifies, for each order  $c$ , the highest sequence number out of the original schedule that has been dispatched before order  $c$  at location  $x$ , i.e., it determines the initial sequence number that is most ahead of its schedule when order  $c$  is dispatched. Term  $(O_c^x - SN_c^x)$  then quantifies the difference versus the current sequence number of order  $c$ , which results in the number of orders that should have been dispatched, but have not been. This number sums up all orders that are unable to enter the next production step because they have either not completed the current production step or the material required for the next production step is not available, in which case dispatching is prohibited. Afterwards, term  $(\sum_{c=1}^C \frac{O_c^x - SN_c^x}{C})$  quantifies the average of the delayed orders during the entire observation period of  $C$  orders. This average is once more divided by  $C$  and the result subtracted from one since this results in a relative measure that quantifies the stability level of the entire observation period.

*Gamma stability level.* The gamma stability level,  $SL_\gamma$ , evaluates the sequence of two consecutive orders in respect of the sequence originally scheduled (Günther, 2017; Lehmann and Kuhn, 2019). This measure belongs to the group of neighborhood-based indicators. It quantifies whether or not an order  $c$  at location  $x$  is scheduled directly behind its originally scheduled predecessor,  $SP_c^x = 1$ , or not,  $SP_c^x = 0$ . Adding up the indicator variable  $SP_c^x$  for all orders of the entire observation period and dividing this number by  $C$  quantifies the gamma stability level.

$$SL_\gamma = \frac{\sum_{c=1}^C SP_c^x}{C} \quad x \in \{1, 2, \dots, P\} \quad (8)$$

*Delta stability level.* The delta stability level,  $SL_\delta$ , is position and neighborhood based and therefore considers both aspects of stability. Hence it cannot be placed in one of the categories introduced since this indicator is some kind of hybrid.  $SL_\delta$  is therefore slightly more complex

to calculate compared to the other indicators. The PM is for example applied at a German automotive company in the premium segment. It counts all orders in case they have remained in their initial position or have been pre-drawn without losing their initial predecessor. As in Eq. 6, those that remain in position are termed  $SV_c^{SD_c^x=0}$ . This means there is a certain relationship with  $SL_\alpha^{SD_c^x=0}$ . The second part is the determination of pre-drawn orders without any predecessors calculated by  $SP_c^{SD_c^x<0}$ , which is a more restrictive version of  $SP_c^x$  used for the gamma stability level. Here the indicators only count wrong predecessors within the early orders. So this indicator can be seen as a combination of  $SL_\alpha^{SD_c^x\leq 0}$  and  $SL_\gamma$ . It focuses on the circumstance that each early order is the consequence of a delayed order. As a result every delayed order is penalized. Since one delayed order is likely to cause many early orders, not all early orders are punished, only the pre-drawn orders. The pre-drawn order can be seen as the first order, which has been moved ahead as result of an order falling behind. It is therefore the successor in the initially planned sequence of currently delayed orders. This means that all early orders, that do not have their initial predecessor are penalized. The results are set in relation to the overall production volume to achieve a relative measure.

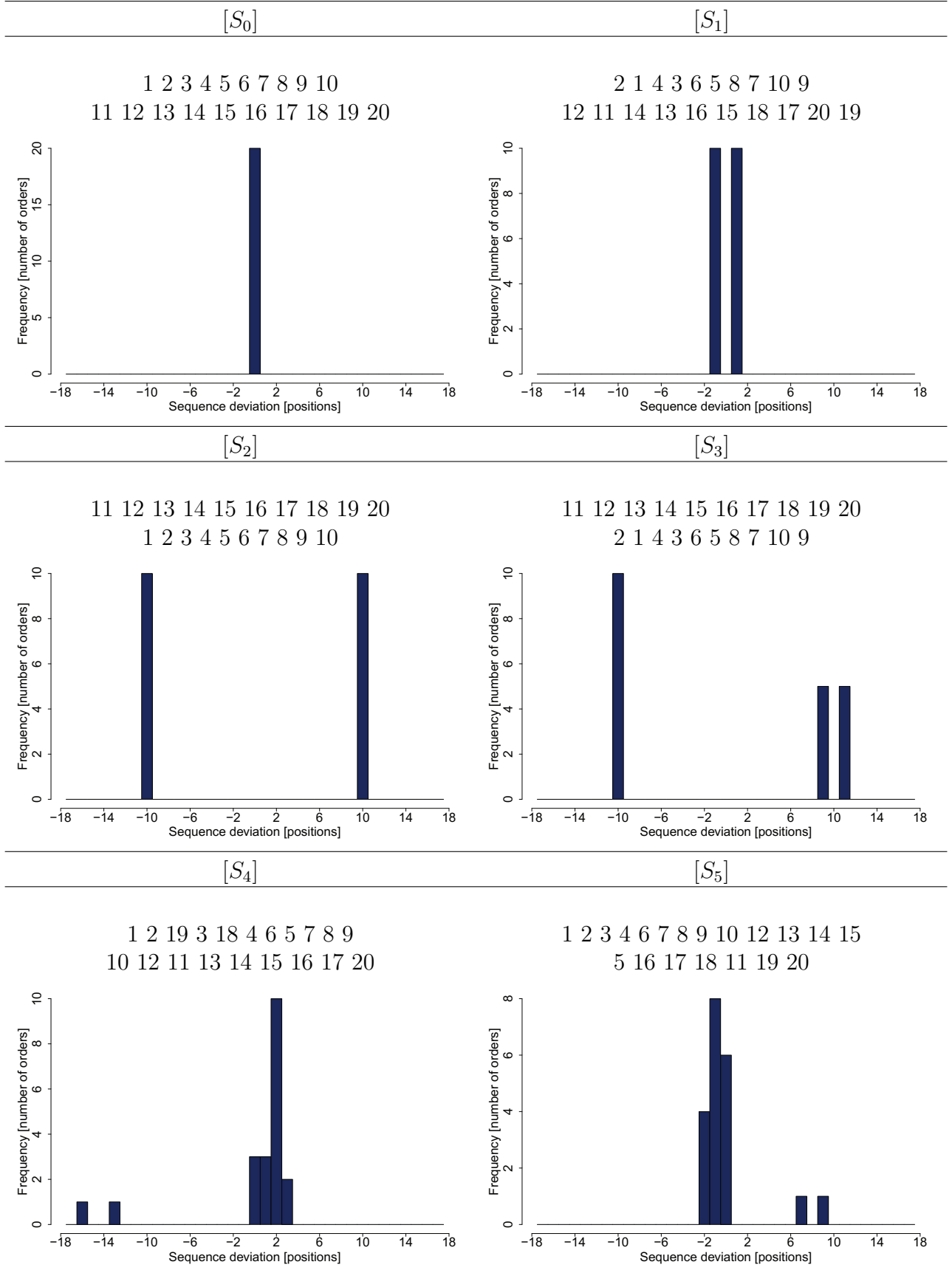
$$SL_\delta = \frac{\sum_{c=1}^C SV_c^{SD_c^x=0} + SP_c^{SD_c^x<0}}{C} \quad x \in \{1, 2, \dots, P\} \quad (9)$$

#### 4.3. Scrambling scenarios

The indicators presented in the previous section are compared and evaluated based on six different scenarios visualized as sequence deviation plots in Table 3. In the following the scenarios are described and ranked based on a resequencing perspective ( $R_B$ ) and from a logistics handling perspective ( $R_H$ ). The resequencing perspective is related to the buffer required to restore the sequence to its initial state. The logistical effort depends on the number of positional deviations.

$S_0$  displays the baseline scenario with the absence of sequence deviation.  $S_1$  is based on a simple swap logic where every car and its direct successor has exchanged its position. In terms of correct succession this sequence is heavily scrambled, meaning that from a logistical viewpoint it is the worst scenario, as each order requires a logistical intervention. From a positional perspective each car only features a minor displacement. This means the car sequence can be restored with a small sized restoration volume. For sequence  $S_2$  the first

Table 3: Scrambling scenarios





half of the initial sequence has been interchanged with the second half. This results in a sequence where most of the initial succession relationships are maintained, but position-wise the sequence is heavily scrambled. From a restoration point of view this sequence is therefore very disadvantageous, but from a material re-sequencing point of view the effort to restore the sequence is manageable since the material can be extracted and reinserted block wise. In scenario  $S_3$  the scrambling methods from the previous two scenarios are combined, meaning that first the two halves are inverted, and then in the first half of the sequence every item is interchanged with its direct successor. Combining both negative aspects, half in each case, from  $S_1$  and  $S_2$  this sequence is unfavorable from a restoration and from a material logistics perspective.  $S_4$  is the worst scenario in terms of required buffer capacity. It features few heavily premature orders and a large number of delayed and slightly scrambled orders. Taking into consideration that orders can only arrive early as a result of their delayed predecessor, this kind of sequence is also considered unfavorable in terms of material logistics since a lot of material has to be stored in the interim. The exact opposite is the case for  $S_5$  where some orders are heavily delayed and the resulting early orders only feature minor scrambling. This reflects average occupancy for the material storage and buffer capacity.

The scenarios are ranked according to their respective suitability for smooth logistics operations  $R_H$  or requiring low buffer capacity  $R_B$ . Table 4 ranks the scenarios from favorable (1) to less favorable (5). Ranking  $R_H$  considers the number of positional deviations as this relates to the additional materials handling effort, while ranking  $R_B$  considers the maximum length of deviation, reflecting the buffer capacity required for resequencing.

Table 4: Ranking of scrambling scenarios

	$R_H$	$R_B$
-	$[S_0]$	$[S_0]$
1	$[S_2]$	$[S_1]$
2	$[S_5]$	$[S_5]$
3	$[S_4]$	$[S_2]$
4	$[S_3]$	$[S_3]$
5	$[S_1]$	$[S_4]$

#### 4.4. Evaluation of stability indicators

To become successfully established, PMs must connect and capture the effort of operational processes (Bourne et al., 2018). To make a statement about the impact of materials

handling and the buffer capacity required, the key figures should reflect the ranking presented. We calculated the indicators introduced previously based on the scenarios described. Table 5 and Table 6 display the results. The range [min/max] exposes the minimum and maximum sequence deviation  $SD_c^x$  and  $\sigma$  standard deviation in the period observed.

Table 5: Evaluation of scrambling scenarios: materials handling

$R_H$	$\sigma$	$SD_c^x$ [min/max]	$SL_\alpha^{SD_c^x \leq 0}$	$SL_\alpha^{SD_c^x \leq z}$	$SL_\alpha^{SD_c^x = 0}$	$SL_\beta$	$SL_\gamma$	$SL_\delta$
[ $S_0$ ]	0	[0/0]	100%	100%	100%	100%	100%	100%
[ $S_2$ ]	10.00	[-10/10]	50%	50%	0%	63.75%	90%	45%
[ $S_5$ ]	2.77	[-2/7]	90%	90%	30%	95.75%	70%	75%
[ $S_4$ ]	4.93	[-16/3]	25%	40%	15%	66%	45%	20%
[ $S_3$ ]	10.02	[-10/11]	50%	50%	0%	63.75%	45%	45%
[ $S_1$ ]	1.00	[-1/1]	50%	100%	0%	97.5%	0%	0%
Rating	-	-	-	-	-	-	+	-

Scale: low relevance [-] high relevance [+]

$SL_\alpha^{SD_c^x \leq 0}$  possesses several disadvantages. It ignores all advanced orders independent of their quality of sequence. The reason behind this assumption is that all early orders are the result of delayed orders, and double penalization should be avoided. But this has low significance for  $R_H$  as advanced orders also have an impact on materials handling depending on their succession. The modification  $SL_\alpha^{SD_c^x \leq z}$  penalizes all positive deviations above a certain level. Variable  $z$  represents the buffer capacity and is set to 1 in this example, i.e., only sequence deviations greater than 1 are counted. It does not represent  $R_H$  in a meaningful way.  $SL_\alpha^{SD_c^x = 0}$  has no significance with regard to the materials handling since there is no distinction of the scenarios possible because half of them are evaluated at zero.  $SL_\beta$  counts the number of orders out of position and has low relevance concerning the materials handling effort. But, as mentioned before, it is a useful indicator to determine the space required for the material handling. This can be seen in scenario 1, which requires a lot of logistical handling (for every single order), but only few (one) logistical space at the time.  $SL_\gamma$  measures whether an order has been released directly behind its originally planned predecessor. It reflects the impact on materials handling effort  $R_H$ . The KPI exactly reflects the ranking and thus, has a high relevance.  $SL_\delta$  considers positive and negative positional deviations with some constraints. The PM has no significance with regard to  $R_H$ . It does not represent the ranking sufficiently.

Table 6: Evaluation of scrambling scenarios: buffer capacity

$R_B$	$\sigma$	$SD_c^x$ [min/max]	$SL_\alpha^{SD_c^x \leq 0}$	$SL_\alpha^{SD_c^x \leq z}$	$SL_\alpha^{SD_c^x = 0}$	$SL_\beta$	$SL_\gamma$	$SL_\delta$
[ $S_0$ ]	0	[0/0]	100%	100%	100%	100%	100%	100%
[ $S_1$ ]	1.00	[-1/1]	50%	100%	0%	97.5%	0%	0%
[ $S_5$ ]	2.77	[-2/7]	90%	90%	30%	95.75%	70%	75%
[ $S_2$ ]	10.00	[-10/10]	50%	50%	0%	63.75%	90%	45%
[ $S_3$ ]	10.02	[-10/11]	50%	50%	0%	63.75%	45%	45%
[ $S_4$ ]	4.93	[-16/3]	25%	40%	15%	66%	45%	20%
Rating	-	-	-	+	-	+	-	-

Scale: low relevance [-] high relevance [+]

As both pre-drawn and delayed orders have an impact on the buffer capacity,  $SL_\alpha^{SD_c^x \leq 0}$  poorly represents the ranking  $R_B$ . Moreover, the intensity of sequence scrambling is important for estimating the buffer capacity.  $SL_\alpha^{SD_c^x \leq z}$  has a high meaning towards  $R_B$ . It counts all orders that are delayed less or equal to 1 cycle. Note that the quality of this KPI depends on the selection of  $z$ .  $SL_\alpha^{SD_c^x = 0}$  counts all deviations but does not measure the intensity, and thus reflects the criteria unsatisfactorily. Apart from one small exception concerning scenario  $S_4$ ,  $SL_\beta$  represents the ranking  $R_B$  properly. It counts the average number of orders out of sequence, which represents the buffer capacity required. The significance of this indicator depends on the type of blocked orders. It does not differentiate whether few orders are out of sequence for a very long time or whether many orders are out of sequence for a short time. Since the first case occurs more frequently due to the nature of the production process, this indicator is meaningful.  $SL_\gamma$  counts gaps in the sequence and shows limited relevance on  $R_B$  since it does not reflect the ranking  $R_B$ . The PM  $SL_\delta$  penalizes all delayed and pre-drawn orders with specific restrictions. The information value is questionable. In principle it represents the ranking but there is one exception concerning scenario 1. In this case the scrambling profile is very beneficial in terms of restoration but the KPI indicates a very unfavorable constellation.

Most of the indicators, although applied in real-world SPSs, do not reflect the desired effects. Only  $SL_\gamma$  truly displays the impact on the materials handling.  $SL_\alpha^{SD_c^x \leq z}$  and  $SL_\beta$  proved to be a good representative of the buffer capacity.

## 5. Application of sequence stability indicators in stabilized production systems

The evaluation of indicators led to a set of appropriate measures. However, the calculations so far are based on exemplary scenarios. For real-world application there are several aspects that have to be taken into account when measuring stability. Data collection, processing and the implementation of sequence-oriented PM cause additional challenges. In this section we will first apply the determined indicators to a real-world data example and bring them into context of short-, mid- and long-term planning horizons. Afterwards, we refer to the obstacles and corresponding solutions of implementing PMs.

### 5.1. Real-world example

Basically there are two major application purposes for key PMs in the context of stabilized production. The first one is short-term oriented for real-time monitoring or daily ex-post reports in order to engage in counter-measures. The others are mid- or long-term observations that evaluate the suitability of the production facility based on repeated daily calculations. Figure 3 shows a typical representation of  $SL_{\alpha}^{SD^z \leq z}$ ,  $SL_{\beta}$  and  $SL_{\gamma}$  on a daily basis. The data set is taken from a German OEM operating in the automotive premium segment. The entrance sequence into the final assembly is compared to the sequence initially planned. We observe 86 production days with roughly 25,000 orders manufactured. The targeted value depends on the underlying assumptions and the infrastructure of the production system. At the facility observed the target value is set at 98 percent, which is also considered a reasonable value in literature (Inman, 2003; Gusikhin et al., 2007). As explained beforehand, the key figures observe a certain period of time represented by a number of orders. For real world application the observation period is usually one day of production. This ranges from 10 units up to over 2.000 units depending on the segment, e.g. luxury segment or mass production. Depending on the operational availability of production shops and varying shift models, the observation period may differ from day to day. Up to ten percent deviation of the weekly production rate can be observed in real-world manufacturing systems (Kotha and Pine, 1994). For this reason relative measures are beneficial, since they ensure comparability. The time series of daily values compared to one overall stability value yields additional information since it reveals the process dynamics and the fluctuation in stability. Observation of long-time series dispose changes in stability due to reorganization of certain areas in production. These time series are usually measured individually for each production step to gain further insight, but the

most important measuring point is at the entrance of the final assembly line. In addition, time series of stability levels can be compared with corresponding time series of buffer filling level (BFL) rework level or missing part level to reveal causal dependencies (see for example Lehmann and Kuhn (2019)). The BFL is the current amount of car bodies inside the buffer which can be used to restore the initial sequence. The level can reach from zero car bodies up to the maximum physical capacity of the buffer.

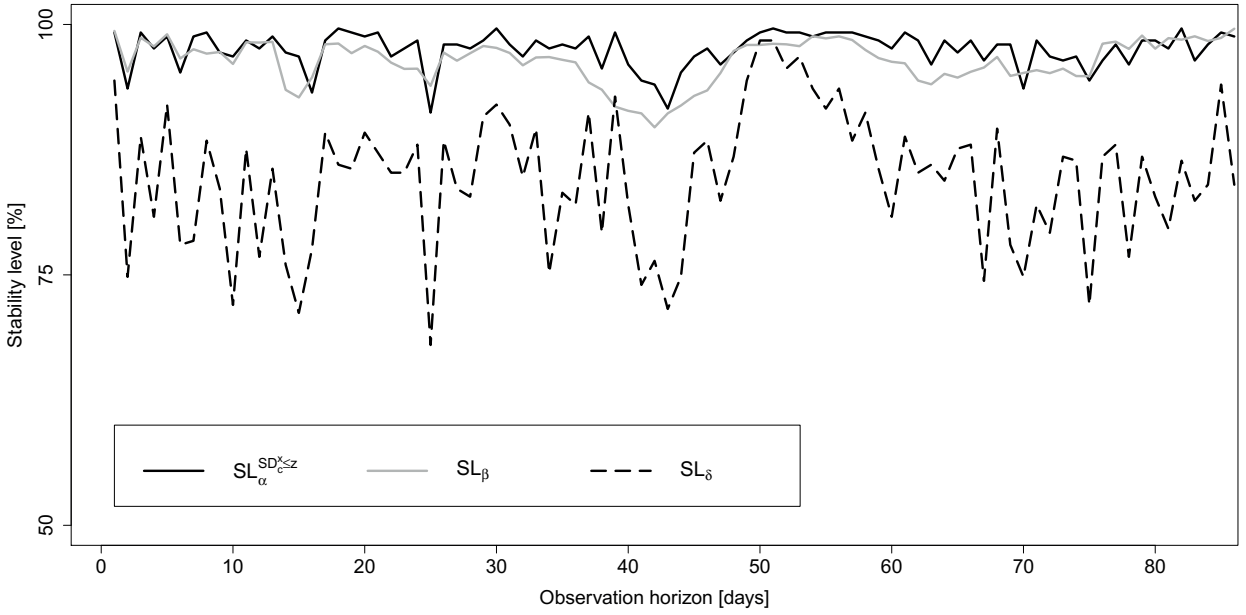


Figure 3: Time series of three different stability measures

### 5.2. Implementation obstacles

When it comes to the application of PMs in real-world production systems several challenges have to be faced that are often not addressed in detail in literature (Bourne et al., 2000). In this section we outline the obstacles we were confronted with while implementing the PMs previously mentioned.

While the initial sequence number is created during scheduling and sequencing of the production volume the current sequence number needs to be calculated in a running production system, which is a difficult task (Alden et al., 2006). To obtain the production data required at relevant points in the CBF, e.g., the entry or exit of a production stage, the current time when the order passes is recorded. This so-called time stamp contains date and time information related to a specific manufacturing step. This is the baseline for all further

calculations. In order to obtain the succession of cars and the corresponding sequence number the orders are sorted by time stamps. Relevant for the measurement of the logistical effort are only orders that trigger JIS/JIT supply. Besides that, there are pre-series cars or other non-standardized car bodies that occupy a production cycle, but are not part of the regular production and materials handling process. These orders are therefore excluded from set  $C$ . Their material is usually provided separately and the assembly is carried out under supervision of engineers. Even though these orders affect the required buffer capacity of the CBF, they are extracted from the data as they can be considered as outliers. Sequence position and cycle number are therefore not the same due to the exclusion of these orders. Approaches for these special cases, i.e. which order has to be removed, have to be determined individually for each production program. Another issue is that there is no guarantee that every single order is tracked correctly during the production process. Reconstruction of missing data causes great manual effort, since each time stamp of the order must be manipulated manually to the actual time of production. To prevent this labor-intensive intervention, complete data collection must be ensured during the operational process. The data must be stored directly from the manufacturing execution system into a data warehouse with an appropriate data architecture. To ensure the utility of the PMs it must be comparable, comprehensible and computable ex post based on the recorded data.

As stated in Section 4 the sum of all sequence displacements need to be zero within one observation period. In automotive practice, however, this assumption is often not fulfilled, since this is only possible for the entire period of production, but not for each observation period, which is commonly one day of production. If this is the case an order from a preceding or succeeding period jumps into the observation period considered. Even small scrambling at the beginning or end of the observation period can lead to interchanged orders between consecutive observation periods, especially when daily or smaller horizons are used as the observation period.

Furthermore, the start and end of the daily observation period varies throughout individual production segments, as the shift models applied differ. For this reason the start and end of the observation period must be defined separately for each segment. A particularly challenging problem is setting up stability measures in a production plant that is already running. Whilst a sequence or at least a cycle number is already implemented, the initial sequence number

is not. Since both of them need a common start to be on the same scale, a restart of the sequence number is required. This is not generally possible without affecting the operational IT systems for the production process. Updating the sequence numbers offline, however, is an appropriate approach to overcome this issue.

### 5.3. Sequence stability indicators related to planning horizons

Even though the goal of operational, tactical and strategic decisions is to improve the stability, the different planning tasks and countermeasures require distinctive indicators. Therefore, simple quantifying operations such as distributions are combined with the three identified stability indicators. The selection criterion for the application of different KPIs is the length of the planning period.

#### 5.3.1. Long-term planning problems

The long-term planning problems of SPSs comprises green field installation of facilities as well as the reconfiguration and transformation of existing plants into stabilized systems. When an SPS is installed for the first time a large variety of planning problems with technical and organizational aspects have to be taken into account. At this stage, the determination of the buffer size and logistics infrastructure is the most important task. Nevertheless, the majority of real-world installation scenarios consist of reconfiguration or adaptation, instead of first-time installation. A reconfiguration is necessary whenever there are substantial changes in the structure of the production setting that influence the distribution of sequence scrambling or the throughput (Lehmann and Kuhn, 2019). E.g., a major change of product assets to introduce electrified power trains. However, the PMs used for the reconfiguration or transformation process remain the same as those applied for first-time installations. The buffer size required to restore a scrambled sequence can be directly estimated from the distribution plotted. The buffer size, for example, that corresponds to the most positive position deviations, i.e.,  $\max_{c \in \{1, 2, \dots, C\}} [SD_c^x]$ , allows reconstruction of the sequence initially planned in all cases (Inman, 2003). The stability measures  $SL_\alpha^{SD_c^x \leq z}$  and  $SL_\beta$  calculated on a monthly-basis are usually used to investigate whether the target stability level is accomplished on a long-term planning horizon. The PM  $SL_\beta$ , for example, can be used for long-term observation to estimate the capacity of the logistical infrastructure. The PMs are usually applied in simulation studies for this type of planning problem.

### 5.3.2. Mid-term planning problems

Mid-term planning problems comprise the production program and initial sequence planning. While the former focuses on matching production resources and demand, the latter determines the succession of models launched down the mixed-model assembly line. Stability-related indicators are usually measured on a daily basis and often plotted as a weekly or monthly time series to detect trends. In addition, the respective scrambling profiles, i.e., distributions  $D(SD_{\{1...C\}}^{x,s})$  of the body shop and paint shop, are plotted taking into account a weekly observation period.  $s$  in this equation represents the start and  $x$  the exit from the body or paint shop, respectively. In this way scrambling sources are identified which facilitates the maintenance of the target stability level. The impact on the logistical handling and effort is represented by  $SL_\gamma$ , which indicates whether corrective steps, e.g., the deployment of additional logistical manpower, need to be taken into account.  $SL_\alpha^{SD_c^x \leq z}$  or  $SL_\beta$  in a weekly or monthly course indicate whether the BFLs are sufficient.

### 5.3.3. Short-term planning problems

The short-term sequencing problem decides on the dispatching of orders at the final assembly line during the production shift or, if necessary, at each cycle. The PMs applied therefore need to explain the current status of the production process instantly. The leeway for making decisions is limited and depends on the number of vehicles available at the buffer and current infrastructural loads. While deciding whether or not to block an order, production control considers the BFL,  $B_{\max}$ ,  $SL_\alpha^{SD_c^x \leq z}$  or  $SL_\beta$  and  $SL_\gamma$ . For short term decisions the most important are the BFL in terms of painted car bodies available and the number of orders blocked already,  $B_{\max}$ , at any given cycle.

The production control ultimately decides whether the state of production allows an order to be blocked. As logistical operations have to be executed when blocking occurs, there is a maximum number, indicated by  $B_{\max}$  or  $SL_\beta$ , that should not be exceeded. It is limited by the size of the logistical area reserved for the storage of these extracted parts and the logistical manpower, measured by  $SL_\gamma$ . Furthermore, blocking caused by missing parts can be substituted by rework and thus avert the blocking of the order. While certain missing parts such as the wiring harness prohibit the assembly of the order, there are some parts that can be installed at rework sections after the final assembly. Line stoppage is another decision option - although extrem - since that type of intervention directly effects the throughput.



But under certain circumstances, for example when a subsequent delivery arrives, a short line stoppage can be reasonable. The production control department balances the trade-off between throughput and sequence stability by taking the PM  $SL_{\alpha}^{SD_c^x \leq z}$  or  $SL_{\beta}$  and  $SL_{\gamma}$  into account.

#### 5.4. Managerial insights

This paper focuses on analyzing and implementing performance measures to effectively operate SPSs. Yet the consequences of reaching certain levels of these indicators have not been explained so far. The remainder of this section focuses on the interpretation of these indicators on a managerial level. From this perspective a high and constant level of stability is desired. Once an order has a scheduled production date the ultimate goal is to attain it. There are two aspects that have a major impact on tying up the production resources: the amount of materials handling and the buffer causes additional costs throughout the complete supply chain. Figure 4 displays the impact. The effect of instability depends on two factors:

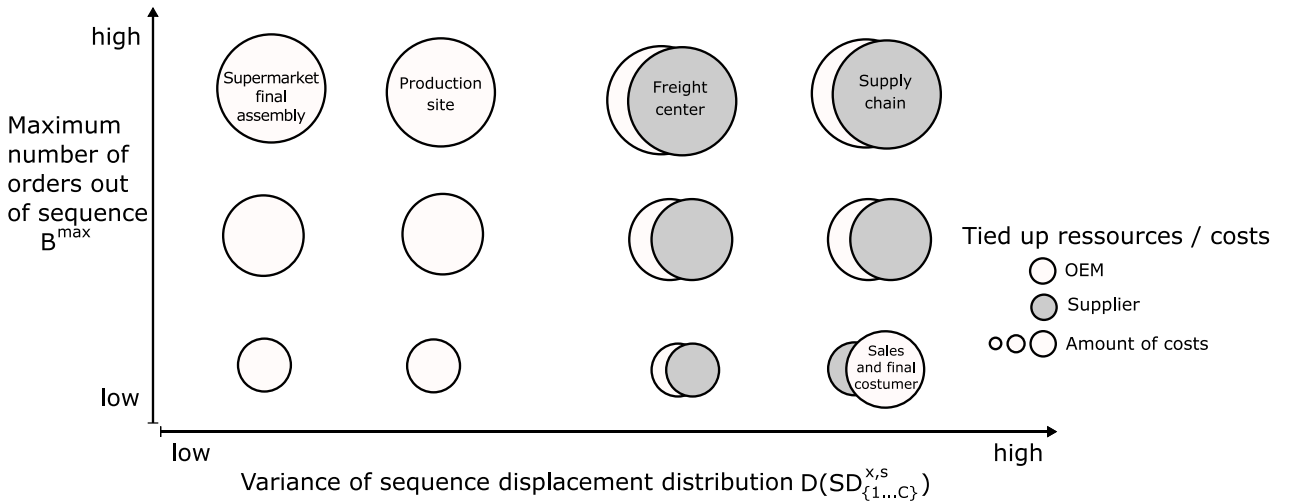


Figure 4: Impact and cost of instability in production networks

the magnitude of sequence deviation ( $D(SD_{\{1...C\}}^{x,s})$ ) and the maximum number of orders out of sequence ( $B_{\max}$ ). In general a high number of orders out of sequence requires high capacity at the OEM to store the material. High sequence displacement will lead to additional materials handling in the upstream supply chain. If a lot of orders are assembled out of their initial planned sequence position in a short time span, this only affects the handling of the material at the final assembly and the storage capacity of the OEM. However, if an order is blocked and assembled much later than initially planned, it has an effect on the materials handling

of the freight center, the supply network and the buffer capacity of the OEM. If delayed by days or weeks, it has an impact on the sales department, as the scheduled delivery date can not be attained. In the worst case the final customer withdraws from the sales contract.

Decoding operational feedback is the foundation for ensuring a constant high stability level. As mentioned in before, traditional production PMs, such as the throughput, are not sufficient to manage SPSs. Simple calculation logic, e.g., standard deviation, are often not enough to express sequence stability in terms of measuring impact on the materials handling and required buffer capacity. The evaluation study conducted on different scrambling scenarios reveals the following: only three indicators adequately reflect these criteria previously mentioned. However, none of these KPIs taken by themselves are sufficient to evaluate all aspects of stability. A set of various KPIs is required to control and operate production. The PMs  $SL_{\alpha}^{SD_c^x \leq z}$  and  $SL_{\beta}$  reflect the buffer capacity required, and  $SL_{\gamma}$  provides information on the materials handling.

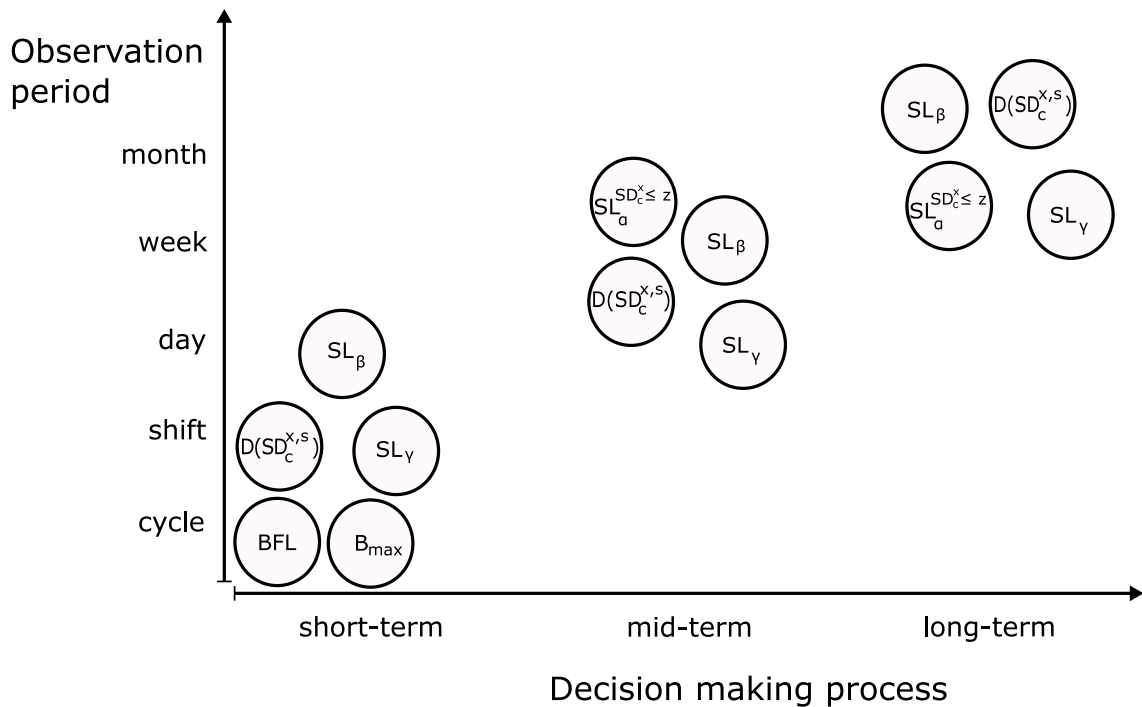


Figure 5: Application of indicators in the planning process

In order to successfully plan and operate stabilized production, system designers must be supplied with relevant information. Different measures need to be taken into account considering the long-, mid- and short-term decision making process. Figure 5 summarizes the set of proposed PMs,  $SL_{\alpha}^{SD_c^x \leq z}$ ,  $SL_{\beta}$  and  $SL_{\gamma}$ , that foster the planning process with

compulsory information. In addition the BFL and  $B_{\max}$ , as well as the scrambling profile based on  $D(SD_{\{1..C\}}^{x,s})$  of the body shop and paint shop need to be tracked. The challenges of implementing these PMs in real-world manufacturing systems are extensive and some OEM's fail during application or operation. Retroactively, the production data cannot be reproduced. Consistency and accuracy are essential for data acquisition and must be ensured for every order. The operational control department and the IT department should conjointly be in charge of storing the correct and informative data for computing the PMs.

## 6. Conclusions and further research

This paper addresses the question of which performance measures are suitable for planning and coordinating production and logistical operations in stabilized mixed-model assembly lines. Car manufacturers establish mixed-model assembly lines along with JIS/ JIT supply approaches to cope with the ongoing trend of increasing variety and outsourcing strategies. These approaches induce the necessity of a stabilized production environment. The benefits of such stabilized systems affect all stakeholders of the supply network. Nevertheless, a high and constant level of stability is required to exploit the advantages of this production system. One of the two major drawbacks are the prerequisites of the system that require sustainable investment, e.g. buffer capacity for restoration. The other one is linked to the dependency on stability throughout the production process and supply chain. Once the concept is established instability causes additional costs. To ensure a high stability level operational feedback has to be transformed into relevant key figures. Six PMs from literature or applied at German OEMs are presented and evaluated based on their relevance in terms of displaying the effort of operational processes. The two criteria selected representing the effort are the amount of materials handling and the required buffer capacity. We show that on its own, none of the PMs presented is sufficient to measure both aspects. One PM turned out to reflect the materials handling well and two quantify the required buffer capacity adequately. Interestingly the most used indicator in practice is not among them. We apply the PMs in a real-world data set to demonstrate the correct application and to enhance awareness of the operational challenges. Furthermore, we set the key figures suggested in relation to the short-, mid- and long-term planning horizon and added further complementary indicators, such as the buffer filling level. The resulting framework makes it possible to successfully configure, balance and

operate SPSs by supporting the selection of meaningful PMs. The proposed performance measures are not restricted to the automotive industry and could be adapted to other mixed model assembly systems. Sectors of industry where build-to-order strategies, high product variety or JIS supply patterns are applied will particularly benefit from SPSs. With some adaptations, the research field can easily be extended to ship, aircraft, train, bus, truck and tractor manufacturing as well as customized engineering industries.

Further research could focus on determining the optimal target stability level of SPSs. To the knowledge of the authors a study on how to estimate the optimal stability level has not yet been conducted. It is determined by the given infrastructure, e.g., buffer capacities and floor space, as well as the production strategies and supply patterns. In literature the target level is set between 95 percent to 98 percent without providing a causal link to the determining factors. The measure of instability in terms of costs also offers several opportunities for future research. Current approaches do not imply financial and qualitative benefits. A study that includes all relevant factors would provide great benefit for decision makers. In addition, analyzing the trade-off between stability level and buffer capacity provided can be a worthwhile research issue.

Recent trends provide possibilities for additional research. A decision framework for design and implementation of automated guided vehicle systems at the final assembly in SPSs needs to be developed. As these systems cause sequence scrambling at the final assembly line, the proposed PMs need to be scrutinized and if necessary extended. On an operational level an important question is how to forecast the stability level within a shift or day. Overall, this field of research leaves plenty of opportunities for further studies.

## References

- Alden, J.M., Burns, L.D., Costy, T., Hutton, R.D., Jackson, C.A., Kim, D.S., Kohls, K.A., Owen, J.H., Turnquist, M.A., Veen, D.J.V., 2006. General motors increases its production throughput. *Interfaces* 36, 6–25.
- Amrina, E., Yusof, S.M., 2011. Key performance indicators for sustainable manufacturing evaluation in automotive companies, in: Zaiyi, G. (Ed.), 2011 IEEE International Conference on Industrial Engineering and Engineering Management, IEEE. pp. 1093 – 1097.
- Beuthner, A., 2018. Profitieren von der Perlenkette. *Automobil-Produktion* 4, 54–55.
- Bourne, M., Franco-Santos, M., Micheli, P., Pavlov, A., 2018. Performance measurement and management: A system of systems perspective. *International Journal of Production Research* 56, 2788–2799.
- Bourne, M., Mills, J., Wilcox, M., Neely, A., Platts, K., 2000. Designing, implementing and updating performance measurement systems. *International Journal of Operations & Production Management* 20, 754–771.
- Boysen, N., Emde, S., Hoeck, M., Kauderer, M., 2015. Part logistics in the automotive industry: Decision problems, literature review and research agenda. *European Journal of Operational Research* 242, 107–120.
- Boysen, N., Flidner, M., Scholl, A., 2008. Assembly line balancing: Which model to use when? *International Journal of Production Economics* 111, 509–528.
- Boysen, N., Flidner, M., Scholl, A., 2009. Sequencing mixed-model assembly lines: Survey, classification and model critique. *European Journal of Operational Research* 192, 349–373.
- Boysen, N., Scholl, A., Wopperer, N., 2012. Resequencing of mixed-model assembly lines: Survey and research agenda. *European Journal of Operational Research* 216, 594–604.
- Cedillo-Campos, M.G., Morones Ruelas, D., Lizarraga-Lizarraga, G., Gonzalez-Feliu, J., Garza-Reyes, J.A., 2017. Decision policy scenarios for just-in-sequence (JIS) deliveries. *Journal of Industrial Engineering and Management* 10, 581.
- Colledani, M., Tolio, T., 2011. Integrated analysis of quality and production logistics performance in manufacturing lines. *International Journal of Production Research* 49, 485–518.
- Das, S.K., Pasan, M.K., 2016. Design and methodology of automated guided vehicle - a review. *IOSR Journal of Mechanical and Civil Engineering Special Issue - AETM'16*, 29–35.
- Dössel, K.F., 2008. In-plant repairs, in: Streitberger, H.J., Dössel, K.F. (Eds.), *Automotive paints and coatings*. 2. ed.. John Wiley & Sons, pp. 377 – 380.
- Fecht, N., 2011. Das Prinzip Perlenkette Porsche. *Automobil Produktion* 11, 24–25.
- Feng, W., Zheng, L., Li, J., 2012. Scheduling policies in multi-product manufacturing systems with sequence-dependent setup times and finite buffers. *International Journal of Production Research* 50, 7479–7492.
- Fournier, X., Agard, B., 2007. Improvement of earliness and lateness by postponement on an automotive production line. *International Journal of Flexible Manufacturing Systems* 19, 107–121.
- Gehr, F., Hellingrath, B., 2007. Vorwort, in: Gehr, F., Hellingrath, B. (Eds.), *Logistik in der Automobilindustrie: Innovatives Supply Chain Management für wettbewerbsfähige Zulieferstrukturen*. Springer-Verlag Berlin Heidelberg. VDI-Buch, pp. VII – VIII.
- Gershwin, S.B., Schick, I.C., 1983. Modeling and analysis of three-stage transfer lines with unreliable machines and finite buffers. *Operations Research* 31, 354–380.
- Göpfert, I., Schulz, M., Wellbrock, W., 2017. Trends in der Automobillogistik, in: Göpfert, I., Braun, D., Schulz, M. (Eds.), *Automobillogistik: Stand und Zukunftstrends*. 3 ed.. Springer Gabler, Wiesbaden, pp. 1–21.

- Grininger, J., 2012. Schlanke Produktionssteuerung zur Stabilisierung von Auftragsfolgen in der Automobilproduktion. FML, Lehrstuhl für Fördertechnik Materialfluss Logistik, München.
- Grininger, J., Meißner, S., 2006. Früh in Reih und Glied. *Automobil Produktion* 11, 54–57.
- Günther, M.T., 2017. Produktionssteuerung nach dem Perlenketten-Prinzip am Beispiel der Automobilfertigung. Friedrich-Schiller-Universität Jena.
- Gusikhin, O., Caprihan, R., Stecke, K.E., 2007. Least in-sequence probability heuristic for mixed-volume production lines. *International Journal of Production Research* 46, 647–673.
- Han, M.S., Park, D.J., 2002. Optimal buffer allocation of serial production lines with quality inspection machines. *Computers & Industrial Engineering* 42, 75–89.
- Hottenrott, A., Grunow, M., 2019. Flexible layouts for the mixed-model assembly of heterogeneous vehicles. *OR Spectrum* 41, 943–979.
- Ilić, O.R., 1994. Analysis of the number of automated guided vehicles required in flexible manufacturing systems. *The International Journal of Advanced Manufacturing Technology* 9, 382–389.
- Inman, R.R., 2003. ASRS sizing for recreating automotive assembly sequences. *International Journal of Production Research* 41, 847–863.
- Inman, R.R., Gonsalvez, D., 1997. The causes of schedule instability in an automotive supply chain. *Production and Inventory Management Journal* 38, 26–31.
- Juran, M.J., 1999. How to think about quality, in: Juran, M.J., Godfrey, A.B. (Eds.), *Juran's quality handbook*. 5 ed.. McGraw-Hill, New York, NY. 8, pp. 2.1–2.18.
- Kern, W., Lämmermann, H., Bauernhansl, T., 2017. An integrated logistics concept for a modular assembly system. *Procedia Manufacturing* 11, 957–964.
- Kotha, S., Pine, B.J., 1994. Mass customization: The new frontier in business competition. *The Academy of Management Review* 19, 588.
- Kuhnert, F., Stürmer, C., Koster, A., 2018. Five trends transforming the automotive industry. URL: <https://eu-smartcities.eu/sites/default/files/2018-03.pdf>.
- Lahmar, M., Ergan, H., Benjaafar, S., 2003. Resequencing and feature assignment on an automated assembly line. *IEEE Transactions on Robotics and Automation* 19, 89–102.
- Lehmann, M., Kuhn, H., 2019. Modeling and analyzing sequence stability in flexible automotive production systems. *Flexible Services and Manufacturing Journal* 192, 349 – 368.
- Li, J., 2013. Continuous improvement at Toyota manufacturing plant: Applications of production systems engineering methods. *International Journal of Production Research* 51, 7235–7249.
- Li, J., Blumenfeld, D.E., Huang, N., Alden, J.M., 2009. Throughput analysis of production systems: Recent advances and future topics. *International Journal of Production Research* 47, 3823–3851.
- Li, J., Blumenfeld, D.E., Marin, S.P., 2008. Production system design for quality robustness. *IIE Transactions* 40, 162–176.
- Lovgren, R.H., Racer, M.J., 2000. Algorithms for mixed-model sequencing with due date restrictions. *European Journal of Operational Research* 120, 408–422.
- Meissner, S., 2009. Logistische Stabilität in der automobilen Variantenfließfertigung. Technische Universität München.
- Meissner, S., 2010. Controlling just-in-sequence flow-production. *Logistics Research* 2, 45–53.
- Meyr, H., 2004. Supply chain planning in the german automotive industry. *OR Spectrum* 26, 343–365.
- Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., Chryssolouris, G., 2010. Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach. *CIRP Journal of Manufacturing Science and Technology* 2, 81–91.

- Müller, M., Burges, U., 2020. Herausforderungen bei der Dimensionierung eines zentralen Entkopplungsmoduls in der Variantenfließfertigung und Darstellung eines selbstregulierenden Kreislaufsystems für Transportmittel., in: Mayer, G., Pöge, C., Spieckermann, S., Wenzel, S. (Eds.), *Ablaufsimulation in der Automobilindustrie*. Springer Vieweg. in Springer Fachmedien Wiesbaden GmbH, pp. 217–229.
- Müller, M., Kuhn, H., 2020. Analyzing a centralized buffer in automotive production plants - a simulation study, in: Xu, X., Dessouky, M.I., Zhong, R.Y. (Eds.), *49th International Conference on Computers and Industrial Engineering 2019 (CIE49)*, Computers and Industrial Engineering. pp. 455–463.
- Neely, A., Plats, K., 2005. Performance measurement system design: A literature review and research agenda. *International Journal of Operations & Production Management* 25, 1228–1263.
- Papadopoulos, H.T., Vidalis, M.I., 2001. Minimizing wip inventory in reliable production lines. *International Journal of Production Economics* 70, 185–197.
- Robinson, L.W., McClain, J.O., Thomas, L.J., 1990. The good, the bad and the ugly: Quality on an assembly line. *International Journal of Production Research* 28, 963–980.
- Rumpelt, T., 2009. Paradox: Stabil und Flexibel. *Automobil Produktion* 23, 34.
- Rumpelt, T., 2010. Prinzip Perlenkette. *Automobil Produktion* 5, 28–29.
- Savsar, M., Al-Jawini, A., 1995. Simulation analysis of just-in-time production systems. *International Journal of Production Economics* 42, 67–78.
- Shin, H., 2000. Supply management orientation and supplier/buyer performance. *Journal of Operations Management* 18, 317–333.
- Standl, M.J., 2016. Daimler knüpft Perlenkette. *Deutsche Verkehrs-Zeitung* 30.
- de Toni, A., Tonchia, S., 1996. Lean organization, management by process and performance measurement. *International Journal of Operations & Production Management* 16, 221–236.
- Wagner, S.M., Silveira-Camargos, V., 2012. Managing risks in just-in-sequence supply networks: Exploratory evidence from automakers. *IEEE Transactions on Engineering Management* 59, 52–64.
- Weyer, M., 2002. *Das Produktionssteuerungskonzept Perlenkette und dessen Kennzahlensystem*. Helmesverl., Karlsruhe.
- Weyer, M., Spath, D., 2001. Das Kennzahlensystem des Produktionssteuerungskonzepts Perlenkette: Chance zur verursachergerechten Ermittlung von Logistikkosten. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*; 96, 116–119.
- Weyer, M., Spath, D., 2009. The production control concept “pearl-chain” – challenges and recommendations for implementing it. *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb* 104, 1126–1130.
- Zeltzer, L., Aghezzaf, E.H., Limère, V., 2016. Workload balancing and manufacturing complexity levelling in mixed-model assembly lines. *International Journal of Production Research* 55, 2829–2844.

# Shared buffer allocation in stabilized automotive production systems

Mareike Müller, Heinrich Kuhn

---

## Abstract

In order to produce mass customized products cost-efficiently automotive manufacturer establish mixed-model assembly lines with just-in-sequence supplying approaches. Production concepts such as the stabilized production system ensure the efficiency and transparency of these complex production sites. To facilitate the stability of the production process buffers are allocated between the body shop and paint shop as well as the paint shop and final assembly. We propose a discrete event based simulation model to examine the impact of a shared buffer on the performance of these production steps in a stabilized production setting. The question is motivated by the assumption that a shared buffer has a balancing effect on stock levels and flexibly exploits buffer capacity. We conduct a simulation study with real-world data of an automotive production site and reveal that a shared buffer supports stabilized production settings. In our case study a constant high stability level is achieved by providing a buffer capacity with the average quantity of  $2/3$  of the daily production output. A series of experiments with downtime reveal the benefit of a shared buffer. Compared to a traditional automotive production with two separate buffers the required buffer capacity is reduced by more than 10 percent. However, a shared buffer introduces new planning problems and requires complex operating policies. Besides the analysis of throughput and the impact of downtime on the stability level, operating strategies are derived from the study.

*Keywords:* Automotive production, Mixed-model assembly line, Shared buffer, Stabilized production system, Discrete event simulation, Empirical case study

---



## 1. Introduction

To cope with the trade-off between strategic flexibility and operational efficiency manufacturer establish mass customization capabilities (Tu et al., 2004). Mass customized products are individually designed products, provided to customers in a timely manner and with close to mass production prices (Pine, 2008). Mass customization requires flexibility, quick responsiveness and its establishing involves a structural transformation in the supply chain (Gunasekaran et al., 2007). But it also provides sustainable competitive advantages (Michalos et al., 2010; Zhang et al., 2019). Although the concept is not linked to a specific industry, the automotive industry became an important representative and driver of development (Salvador et al., 2008; Walcher and Piller, 2012; Kortmann et al., 2014). Car manufacturer increasingly consider the heterogeneity of customers' needs as a business opportunity (Volling, 2009). Digital tools such as car configuration systems have been developed to facilitate customers to individualize their order (Herlyn, 2012). Recent developments in technology, e.g., electrical drive, and shifting societal demands enhance the product range even further (Kuhnert et al., 2018). Furthermore to scale globally original equipment manufacturers (OEMs) need to overcome market entry barriers, which often occur in form of regulations and increase the number of possible variants (Ito and Sallee, 2018; Hoffmann, 2018). Recognizable effects of these developments are a wide range of car models on offer and a growing number of parts to be handled in supply chains and at assembly lines.

To face these challenges most manufacturer combine a mass customization strategy with mixed-model assembly lines (MMAL) in a stabilized production environment (Müller et al., 2020). Several products with customized features are produced cost efficiently on one flexible assembly line (Boysen et al., 2008). A build-to-order strategy combined with a fixed production sequence allows to plan the manufacturing date of each order to the minute (Müller and Kuhn, 2020). The sequence is transferred to suppliers and sub-suppliers which enables the implementation of lean material flow concepts such as just-in-sequence (JIS) delivery (Weyer, 2002). To successfully apply these strategies production processes need to be stable and the schedule of customer orders reliable. There are two effects which reduce the stability level: unreliable production lines and sequence scrambling. Dynamic behavior of two succeeding production steps without compensating work in progress (WIP) result in blocking and starving and cause capacity losses (Conway et al., 1988). Sequence scrambling is caused by differing

processing times, rework and blocking of scheduled orders (Müller and Kuhn, 2020). To allow unreliable production sections to operate independently buffers are established between production steps. They are also used for arranging the sequence and to ensure a specific production mix. Buffers increase production efficiency, reduce overall costs and keep the production and its material running smoothly. But the installation is expensive, occupies space and increases the WIP. In comparison to linear aligned buffers, a shared buffer has a balancing effect on stock levels and flexibly exploits buffer capacity. As a result it decouples the production process with a smaller buffer size, occupies less floor space and it can reduce investment cost. But the car body flow (CBF) changes and the latitude for decision enlarges with a shared buffer. It is questionable whether a shared buffer covers all requirements of a real-world stabilized production system (SPS). Analytic approaches on allocation of buffer space in flow lines are subject to limitations and restricting assumptions. Discrete event simulation (DES) serves as a decision support system for participants to improve real-world production settings (Banks, 1998; Alfieri and Matta, 2012). DES is used for efficient if-then-else analyses of different alternatives and is well-established to model complex real-world manufacturing systems (Zeigler et al., 2010). We use a DES approach with the current production setting of a German OEM and model a shared buffer. This study is based on the preliminary work of Müller and Burges (2020) and provides further results and operating policies of a shared buffer. We show which buffer functions are covered by the shared buffer, the optimal filling ratio of unpainted and painted car bodies and required production control policies. Beneficial effects of a shared buffer become particularly apparent in scenarios with differing production speeds and downtime. In our case study a shared buffer reduces the total buffer capacity by 11 percent compared to a system with two separate buffers.

The paper is structured as follows. Section 2 gives an overview of stabilized automotive production systems and introduces concepts to allocate buffers in stochastic flow lines. Section 3 provides related literature and reveals research gaps where research questions (RQ) are derived from. Characteristics of the production process and applied performance measure are introduced in Section 4. In Section 5 proceedings of the simulation study, the modeling approach and validation are displayed. Results along with a discussion on recommendations are covered in Section 6. Managerial insights are given in Section 7. A summary and prospects for future research in Section 8 conclude the paper.

## 2. Buffer planning in stabilized automotive production systems

This section is divided into two parts: automotive production and buffer capacity planning. We give a short overview of automotive production, specific requirements of MMAL in stabilized production environments and sources of instability. The second part includes a description of buffer functions, types and requirements of shared buffers.

### 2.1. Automotive manufacturing

*Stabilized production system.* An automotive manufacturing site consists of production steps and buffer systems which are sequentially organized and physically connected by conveyor belts. Transport devices (skids) are used to transfer car bodies on conveyor belts and to store them in buffer areas. Production steps comprise the sheet metal shop, body shop, paint shop and final assembly line. The degree of vertical integration differs heavily among OEMs. Typical fields for outsourcing are the sheet metal shop, saddlery, axle assembly, power train and all logistical operations (Krcal, 2008). The sheet metal shop produces the components for joining the car body. These components are usually manufactured in batches and the production unit is decoupled by a buffer (Spieckermann et al., 2000). After the joining process in the body shop the car body enters a buffer area. Afterwards it is transferred to the paint shop where color layers are applied in several steps (Dössel, 2008). The painted car bodies are passed on into a buffer in front of the final assembly. This buffer contains painted car bodies covering the assembly volume of some production hours up to several shifts, depending on the type of production system.

A built-to-order manufacturing approach is commonly found in industry with highly customized products (Meyr, 2004). E.g., in German automotive manufacturing more than 60 percent of cars are built to customer order. The production process of individualized orders starts when the confirmed order is received (Holweg et al., 2005). The quantity of potential car configurations at the final assembly grows exponentially since customers can combine and add features with only few restrictions. Thus, theoretical product variety exceeds several billions (Holweg et al., 2005). Variability in option content has a significant adverse impact on assembly line downtime, repair of stations, rework of car bodies and inventory levels (Fisher and Ittner, 1999). Furthermore, it causes a raise in complexity within the manufacturing process and supply chain (Boysen et al., 2011). The growing number of parts that are handled at assembly lines have a negative effect on the level of required buffer capacity (Lehmann

and Kuhn, 2019). Since space close to the production site is limited and shortfalls of missing parts expensive logistical activities become the center of attention. One approach to reduce inventory and optimize the production as well as material flow is implementing JIS supplying strategies in a MMAL environment. MMAL are established to produce various customized products on flexible production lines (Boysen et al., 2008). These approaches are well established in automotive manufacturing systems and give rise to a number of decision problems (Inman and Bulfin, 1991; Boysen et al., 2015). A fundamental requirement for optimized material supplying approaches is stability in the production process (Lehmann and Kuhn, 2019). First descriptions of the stabilized production concept in literature go back to the nineties (Morrison, 1991; Sawyer, 1994; Voller and Kistler, 1997). Since then core ideas of the SPS have been adopted by many OEMs worldwide and all German premium car manufacturers (Müller et al., 2020).

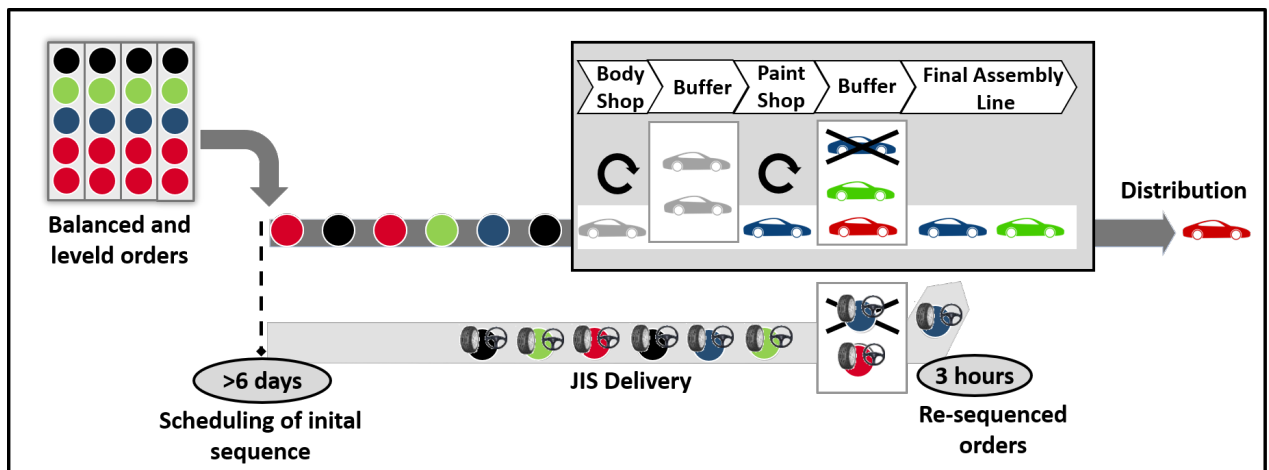


Figure 1: Automotive manufacturing system in stabilized production environment

Figure 1 shows the production process of an OEM with an established SPS. Key point of this concept is a production sequence consisting of customer orders, which are fixed several days before the beginning of the manufacturing process. As soon as an order is received from a customer it is sorted into production days. These level indicators guarantee that each production day already represents a balanced model mix. In our example every production volume contains the same amount of red, blue, green and grey orders. About six days before the start of the assembly process orders are arranged into the sequence initially planned which is communicated towards JIS suppliers. At the beginning of the body shop these orders are assigned to car bodies. The sequence of car bodies gets scrambled during the production

process. The buffer in front of the final assembly is used to re-sequence the initially planned sequence. Some hours before the start of production the re-sequenced car bodies are fixed for the final assembly. Orders are prioritized according to the sequence initially planned. Those which are not manufactured at their original planned position, e.g., the blue car body, provoke modifications in the production sequence. The JIS material flow has to be adapted accordingly, which requires storage space and handling operations. Thus, the intensity of scrambling is linked to logistical costs and needs to be carefully measured and observed. It is only possible to effectively apply lean delivery concepts or car sequencing approaches if the stability level of the production process exceeds a certain level.

*Instability in automotive production systems.* Especially high volume production sites struggle to successfully establish stabilized production concepts (Womack et al., 2006; Lehmann and Kuhn, 2019). It is therefore inevitable to analyze sources of instability in the CBF. On MMALs products move sequentially from one work station to another (Gershwin and Schick, 1983). Due to machine breakdown, variations in process times and blocking of machines as a result of different part routing, flow lines have a dynamic behavior (Mahadevan and Narendran, 1993; Burman et al., 1998). Manufacturing stations can be in different states: busy, idle or blocked due to different causes. During the busy period the station is working. When the production process is forced to stop because of no available car bodies from the upstream process, the production station is idle and the production flow is starving. This condition is also caused by missing or defective material. Blocking occurs when a completed workpiece cannot be moved because the downstream station is busy, full or under repair (Papadopoulos and O’Kelly, 1993).

An additional source of instability in SPSs is the scrambling of the sequence. When car bodies leave the production flow and enter additional or parallel process steps they fall behind or pull ahead which results in scrambling (Inman, 2003). Defective car bodies are tagged and transferred to repair loops or off-line repair stations. Line-stop or zero-defect strategies avoid sequence scrambling because the assembly line stops until the rework is finished (Robinson et al., 1990). A stop inevitably leads to losses in production volume. The length of the flow line and the characteristics of the production system plays an important role while considering the best handling strategy. Car bodies with major rework or missing parts due to a supply bottleneck are blocked for a long period of time. E.g., if a car body has to be reassembled the

replenishment time is at least as long as the production lead time plus, if required, the time to reorder parts. Another source for scrambling is random downtime of parallel machines, missing parts or outage of material. Production-induced varying lead times for models, body styles and equipment features also cause scrambling. One specific source of scrambling in stabilized MMAL are differing sequences initially planned of subsequent production steps. The body shop, paint shop and final assembly often do not share one optimal sequence. E.g., whereas in the body shop two consecutive convertible cars are not allowed there is no limitation in the following production steps. This raises the need to re-sequence jobs upon leaving a production steps and before entering the next one (Lahmar et al., 2003).

## *2.2. Buffer capacity planning*

In order to implement buffers in SPSs efficiently a number of long-term planning problems must be considered. They include considerations on buffer types, buffer functions, capacity as well as additional requirements of stabilized production settings.

*Buffer types.* Potential layout designs of complex production systems include parallel lines and closed-loop buffer systems (Li et al., 2009). In automotive production there are commonly three types of buffers used (Sörensen and Gerrit K. Janssens, 2001; Inman, 2003; Lim and Xu, 2009; Boysen and Zenker, 2013; Alszer et al., 2017). As illustrated in Figure 2 they can be subdivided into the following categories: transfer buffers, buffers with restricted access and automated storage and retrieval system (AS/RS). A transfer buffer decouples two successive production steps without the possibility of changing the sequence. Restricted buffers such as mixed banks with parallel or loop lines and pull-off tables are subject to limited removal strategies (Lahmar et al., 2003; Spieckermann et al., 2007; Ding and Sun, 2004). Control mechanisms, e.g., the input strategy of the incoming car bodies play an important role to ensure the necessary flexibility in the withdrawal of these car bodies. In the example (a) and (b) of Figure 2 it is not possible to retrieve a blue car because access is prevented by other car bodies. An AS/RS guarantees that a buffered car body can be released at any position of the sequence (Boysen and Zenker, 2013). But these systems require higher capital investment and need more floor space than alternative storage systems.

*Buffer functions and capacity planning in stabilized production.* Buffers in series production lines with stochastic processing times and unreliable stations perform different functions.

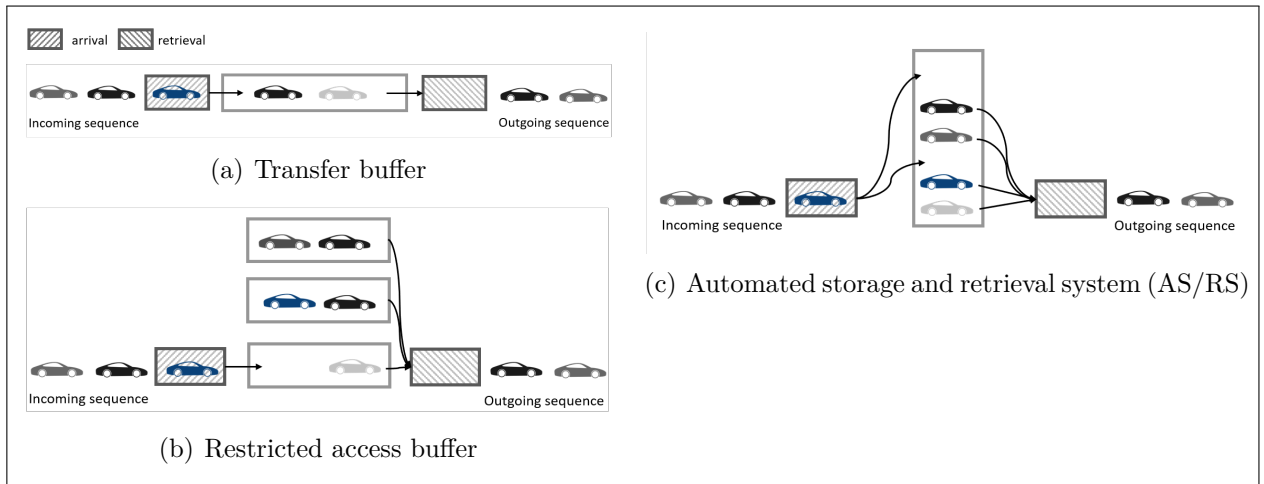


Figure 2: Examples of buffer types

Buffers filled with WIP and empty places enable different production, breakdown and repair rates (Wijngaard, 1979). In the case of automotive production flow these functions can be further specified. Foremost, buffers filled with WIP mitigate throughput losses by decoupling the body shop, paint shop and final assembly. They prevent idle or blocking states when the upstream or downstream production step interrupts the production flow. Furthermore, WIP and empty buffer places enable different production speeds and asynchronous shift models. In production systems with specific control strategies such as an SPS WIP is required for scheduling, order re-sequencing or to realize dispatching rules. Empty places in the buffer are needed to store blocked orders, e.g., if a car body cannot be set up at its scheduled sequence position due to missing parts or quality problems. Different amount of WIP is required to map these functions. A schematic illustration of the functions linked to the WIP in the buffer is displayed in Figure 3. The buffer size to decouple production steps [1] depends on the number and length of downtime and interruptions. To smooth different production speeds [2] buffer capacity in the amount of the maximum difference of output of two successive production steps during one shift is required. The specific z-shaped curve occurs if an upstream or downstream production step works in different production speeds than the preceding or subsequent step, respectively. A volume of car bodies is stored to compensate scrambling effects of upstream production steps [3]. The required capacity depends on various factors such as scrambling, model mix, sequencing rules and minimum spacing restrictions. The size of the buffer to restore the sequence to 100 percent depends on the car body with the greatest delay (Inman and Schmeling, 2003). Therefore the WIP in the buffer must be equal or greater than the

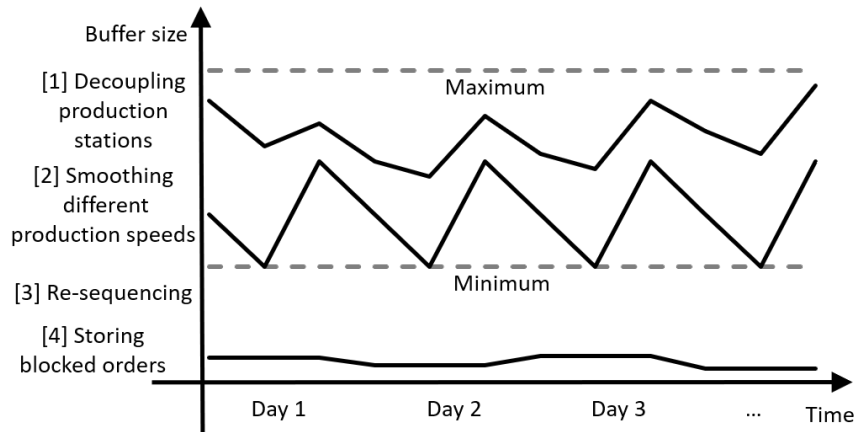


Figure 3: Buffer filling level with WIP performing different functions

greatest sequence displacement. A car body can be delayed in the production flow by shifts or days, e.g., due to major rework or the car body gets scrapped. This can take several days and would mean that the buffer has a correspondingly capacity of the throughput of several production days. It is therefore almost impossible to re-sequence the sequence originally planned entirely. The maximum number of car bodies that are blocked at the same time determines the capacity for storing blocked orders [4].

The number of shelf compartments specify the maximum filling level. It should be equal or greater than the required capacity for functions [1]-[4]. The height of the minimum filling level is variable. It depends on the steering logic of the production system. If the buffer filling level drops below the amount of [1]-[2], e.g., during a major downtime in upstream production steps, the re-sequencing volume [3] decreases. There are two options to manage the production system in that situation. The final assembly stops until upstream steps fill up the buffer which leads to throughput losses. Or the production system runs with a capacity below the minimum which means that control strategies are not executed properly. In SPSs this has a negative impact on the material handling at the final assembly, the balancing of the production mix and the supply chain. Thus, there is a trade-off between throughput losses and deterioration of control strategies. Both options cause additional costs and the production control should carefully weighing those up.

*Shared buffers in stabilized production systems.* On the left-hand side of Figure 4 an typical SPS with production steps and buffers is displayed. SPSs are commonly linear aligned, i.e., the outgoing/ incoming sequence map the production flow and are clearly connected (Inman,



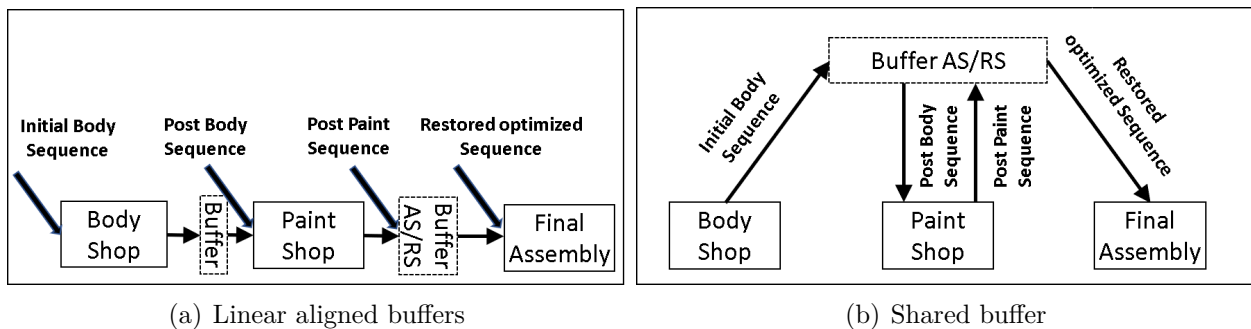


Figure 4: Buffer systems in stabilized production systems

2003). Car bodies pass through the system in a predetermined order. The sequence initially planned is scrambled and re-sequenced at buffer areas (Choi and Shin, 1997). Commonly an AS/RS buffer is installed between the paint shop and final assembly to enable full range of re-sequencing (Lehmann and Kuhn, 2019; Müller and Kuhn, 2020).

A shared buffer has a balancing effect on stock level and enables to fully utilize its capacity. It leads to an increase of throughput (Matta et al., 2006). But the CBF changes which shapes a new system architecture as shown in Figure 4 right-hand side. It results in new challenges for system designers when allocating buffer functions and planning the production flow. As all car bodies pass through the shared buffer twice the processing time inside the buffer is increased which can turn the transfer system into a bottleneck. Too slow transfer mechanism or an excessive number of skids reduces throughput (Tempelmeier and Kuhn, 1993). Technical requirements and control strategies must be taken into account to keep all required functions running. Thus, a shared buffer has an impact on the short-term decisions of the shop-floor production control. In order to avoid system-dependent losses in throughput, strategies for transportation and the optimal number of transport devices must be determined (Buzacott and Yao, 1986). If the shared buffer converges towards the maximum filling level, e.g., during a long downtime of the final assembly, the preceding production steps compete for the remaining buffer capacity. Mechanism are necessary to control the release of car bodies into manufacturing lines and to authorize production steps to produce.

### 3. Related literature and research question

In order to implement and operate a shared buffer in SPSs efficiently, both long-term and short-term planning problems must be considered. Long-term planning problems include design, allocation and capacity of buffer in alignment with infrastructural requirements of the

stabilized production setting. Short-term planning problems comprise buffer management and production control.

The buffer allocation problem (BAP) has been extensively examined over the last decades and opens a wide range for research (Buzacott, 1967). Most publications on the BAP in manufacturing systems are under the objective of throughput maximization or the minimization of the buffer size (Demir et al., 2014; Zhang and Matta, 2020). Only few studies solve the BAP under more than one objective or distinguish buffer functions in their analysis (Weiss et al., 2018). The assumptions presupposed in the literature often do not meet the practical requirements of production settings. E.g., the capacity of real-world buffers is usually limited by means of the infrastructure, but finite buffers are rarely considered in literature (Gusikhin et al., 2008; Macgregor Smith and Cruz, 2005). Only few contributions can be found on the subject of allocating shared buffers in production lines. The question if the storage should be locally or centrally assigned is one component of the generic flexible manufacturing system (FMS). Most of the FMS approaches focus on intermediate storage capacity with a single product or a central storage in a system with one machine to produce  $m$  products in batches (Buzacott and Yao, 1986; Houshyar, 1991). The question of a central buffer in FMS is considered by Tempelmeier and Kuhn (1993). To estimate the blocking and starving of systems with a central buffer restricting assumptions are applied. E.g., the capacity of the buffer is assumed to be equal to the number of pallets or transport devices in the system.

The BAP is an important requirement to design stabilized manufacturing systems and ensures a continuous flow of production (Enginarlar et al., 2005; Womack et al., 2006). Inman (2003) presents an approach to calculate the optimal size of an AS/RS buffer to re-sequence scrambling effects with and without order decoupling concepts. A method to attain a desired throughput with leanly operated buffers are presented by Ding and Sun (2004). Meyr (2004) reviews methods of Operations Research to support the various planning tasks, e.g. buffer sizing, involved in supply chain planning of the German automotive industry. Fournier and Agard (2007) introduce a postponement strategy and vehicle re-sequencing with intermediate buffers between each production step. Meissner (2010) introduces an approach to hedge against sequence instability of production processes by means of physical or virtual re-sequencing buffers. Boysen et al. (2012) reviews existing research on re-sequencing in a MMAL context with physical buffers and virtual re-sequencing strategies. Singholi (2015)

use a simulation method to investigate on the factors affecting the average delay at buffers in an FMS with scheduling rules. Rybicka et al. (2016) use a discrete event simulation to optimize the production line in a FMS environment in the automotive industry. Günther (2017) provides different re-sequencing strategies with line buffers in the context of the SPS. Cedillo-Campos et al. (2017) propose an algorithm to evaluate different decision policy scenarios by considering buffers to reduce risks of supply disruptions at assembly lines. Lehmann and Kuhn (2019) analyse the transformation of high volume automotive production sites to the basic concept of stabilized production. Literature survey on studies of buffer allocation in stabilized production settings reveals that intermediate buffers are the center of investigation. So far, there is no study on shared buffers in automobile manufacturing (Boysen et al., 2012).

In short-term shop-floor production control buffer management plays an important role. It provides control on lead time and indicates necessary improvements on the shop-floor (Hurley, 1996). The dispatching and scheduling of car bodies as well as the reaction to disruption are part of the short-term decision making process (Papadopoulos and Heavey, 1996). In linear aligned production systems flow control mechanisms, e.g., Kanban or CONWIP policies, are applied (Gstettner and Kuhn, 1996; Graves et al., 2007; Junior and Filho, 2010). Research on Kanban controlled lines mostly focuses on elements of linear aligned buffer system design, sequencing and batch sizing (Berkley, 1992). Furthermore, none of the current literature combines production control of a shared buffer with the requirements of SPSs.

Various types of problems, modeling and solution methods on BAP are available. Methodological approaches to solve the BAP include dynamic programming, search methods and metaheuristics (Weiss et al., 2018). These methods are less applicable for real-world production settings because of restrictive assumptions and limitations. Typical assumptions to reduce complexity are stationary behaviour, a single-product manufacturing system, infinite buffer capacity or short assembly lines with 3 to 5 work stations. Furthermore, existing models only depict certain functions of linear aligned buffers. Steering or sequencing rules, which have a major impact on the required capacity, are often neglected. While these pure optimization problems are interesting for production line designers whenever there are physical and/or technical constraints regarding re-allocation of certain system resources, a simultaneous optimization of the allocation provides more flexibility and a higher performance improvement potential. A multi-objective approach to simultaneously plan the buffer capacity is required.

For this reason, we propose a discrete event based simulation model. Its approach suits the particular requirements, such as including the working schedules, factory calendar and the transferring into subsequent sequences. A simulation model facilitates both, the design and as well as the operational management of a shared buffer.

Since the available literature does not cover all aspects of a shared buffer in SPSs there are several opportunities for research. Goal of this article is to answer the following research questions (RQ):

- RQ1 What is the relationship between buffer filling level and sequence stability? Which buffer filling levels of unpainted and painted car bodies should be selected assuming a predefined level of stability?
- RQ2 How do different production speeds and downtime affect the system behavior?
- RQ3 Which production control policies are required in an SPS with a shared buffer?

#### **4. Performance measures and empirical analysis of the production process**

In order to answer the above mentioned research questions key performance indicators (KPIs) to measure the performance and stability of the system are necessary. Furthermore, we examine a real-world data set and depict scrambling characteristics of the production steps in detail.

##### *4.1. Measurements to evaluate production performance*

Throughput, buffer filling level and stability are important indicators to evaluate the performance of SPSs. In this context, stability is the polar opposite of instability or scrambling. Stability measures should quantify the impact of scrambling on material handling and required buffer capacity at production steps where JIS concepts are applied. Müller et al. (2020) give a comprehensive overview on KPIs in SPSs. We apply traditional KPIs as well as two basic and one relative stability indicator which are classified for long- and short-term decision making. The notation is summarized in Table 1. These indicators appeared to be relevant and are applied at the OEM where the case study takes place. It ensures comparability of simulation experiments with real-world observations and the interpretation of simulation outcomes by practitioners.

Variable	Description	Definition
$C$	Number of orders within the observation period	$\{1, 2, \dots, c, \dots, C\}$
$P$	Number of steps (locations) of the entire production process. $bx$ = body shop exit; $pa$ = paint shop access; $px$ = paint shop exit; $fa$ = final assembly access	$\{1, 2, \dots, x, \dots, P\}$
$N$	Number of sequence numbers of the observation period	$\{0, 1, 2, \dots, n, \dots, N\}$
$T$	Cycle	$\{1, 2, \dots, t, \dots, T\}$
$SN_c^x$	Sequence number of order $c$ at production location $x$	$\{1, 2, \dots, N\}$
$SN_c^0$	Originally scheduled sequence number of order $c$ ; $SN_{c=0}^0 = 0$	$\{1, 2, \dots, N\}$
$SD_c^x$	Sequence deviation of order $c$ at location $x$ compared to the sequence originally scheduled	$SN_c^x - SN_c^0$
$B_{\max}$	Maximum amount of orders $c$ simultaneously out of position in period $C$	$\max_{c \in \{1, 2, \dots, C\}} [O_c^x - SN_c^x]$
$O_c^x$	Maximum of the original sequence numbers of all orders dispatched before order $c$ at location $x$	$\max_{d \in \{1, 2, \dots, C\}} \{SN_d^0   SN_d^x \leq SN_c^x\}$
$BFL_t^{up}$	Buffer filling level of unpainted car bodies $up$ of cycle $t$	$\{0, 1, 2, \dots, BS\}$
$BFL_t^p$	Buffer filling level of painted car bodies $p$ of cycle $t$	$\{0, 1, 2, \dots, BS\}$
$BS$	Buffer size	$\mathbb{Z}^+$

Table 1: Notation

*Long-term stability measure.* A simple but efficient measure to estimate the amount of scrambling in the long-term is the sequence displacement (Inman, 2003). Each customer order  $c$ ,  $c \in \{1, 2, \dots, C\}$  is associated with a sequence number, denoted as  $SN_c^x$  with  $SN_c^x \in \{1, 2, \dots, C\}$ , referring to their position in the sequence at a specific step (location) in the production process, i.e.,  $x$ ,  $x \in \{0, 1, \dots, P\}$ , respectively. The originally planned sequence number is referred to as  $SN_c^0$  with  $SN_c^0 = c$ . The deviation of the sequence position of order  $c$  between location  $s$  and  $x$  is achieved by subtracting the reference sequence number of order  $c$  at location  $s$ ,  $SN_c^s$  from its sequence number at location  $x$ ,  $SN_c^x$ .  $SD_c^{x,s}$  displays the magnitude of sequence deviation an order has suffered. A negative value of  $SD_c^{x,s}$  indicates that order  $c$  is moved ahead. A positive value results if order  $c$  has fallen behind.

$$SD_c^{x,s} = SN_c^x - SN_c^s \quad 0 \leq s < x, \quad s, x \in \{0, 1, \dots, P\}, \quad c \in \{1, 2, \dots, C\} \quad (1)$$

To determine the scrambling within a specific production stage not one single value of  $SD_c^{x,s}$  is used but all values from the observation period  $C$ . The distribution is commonly referred to as scrambling profile. It is displayed as absolute distribution  $D(SD_{\{1\dots C\}}^{x,s}) = \{f(a_1), \dots, f(a_j)\}$  with  $(a_1, \dots, a_k)$  being the realizations of  $SD_c^{x,s}, c \in \{1, 2, \dots, C\}$  and  $f(a_j)$  being the frequency of  $a_j$ . For the entire number of orders considered ( $C$ ) the values of  $SD_c^{x,s}$  add up to zero and the mean of all values  $SD_c^x, c \in \{1, 2, \dots, C\}$  is also zero.

The KPI beta stability level ( $SL_\beta$ ) estimates the average required buffer capacity for blocked orders and determines the corresponding logistical storage space for its material (Müller et al., 2020). It is used for long-term observation to estimate the capacity of the logistical infrastructure and is therefore suitable for simulation studies.  $SL_\beta$  quantifies for each order  $c$  the highest sequence number out of the original schedule, which has been dispatched before order  $c$  at location  $x$ . The higher the value, the more stable is the system. The term  $(O_c^x - SN_c^x)$  is referred to as  $B_{\max}$  and quantifies the difference to the current sequence number of order  $c$  which results in the number of orders which should have been dispatched, but have not. The average storage capacity required during the entire observation period of  $C$  orders is quantified as  $(\sum_{c=1}^C \frac{O_c^x - SN_c^x}{C})$ . The average usage of buffer capacity is divided by  $C$  orders and the result subtracted from one.

$$SL_\beta = 1 - \frac{\sum_{c=1}^C \frac{O_c^x - SN_c^x}{C}}{C} \quad x \in \{1, 2, \dots, P\} \quad (2)$$

*Short-term measures.* When dispatching or blocking orders at the final assembly production control has to consider suitable indicators to resolve several trade-offs. The  $BFL_t^p$ ,  $B_{\max}$ , the throughput, the occupancy rate of the rework section, the rework time needed, the priority of the order and the observance of sequencing rules are the most important indicators for short-term decisions.

As logistical operations have to be executed when an order is blocked, there is a maximum number of blocked orders  $B_{\max}$ , which should not be exceeded.  $B_{\max}$  describes the required storage capacity for the extracted car bodies and parts of blocked orders and is limited by the size of logistical area reserved for this purpose. The example of Figure 5 left-hand side displays a dispersion where in over 90 percent, a maximum of 2 vehicles are blocked at the same time. It is important to take into account, that in an SPS at the final assembly it is

not allowed to produce a single order in advance. Each delayed order brings the sequence forward by one position. E.g., if the throughput rate is 12 units per hour and  $O_c^x$  equals 6, production slots are rescheduled and orders are produced 30 minutes earlier. This also affects the CBF and its material as their supply is pulled forward. Once production control gives the go-ahead for the blocked orders and  $O_c^x$  is reduced this effect turns back.

The  $B_{\max}$  does not provide information about the length of an individual blocking. For this purpose the  $D(SD_{\{1..C\}}^{x,s})$  should be examined. Both examples in Figure 5 right-hand side are possible dispersions resulting from  $B_{\max}$ . In example (b) some cars are blocked for more than 2 cycles causing others to overtake. In example (c) the dispersion is narrow, more than 70 percent of cars are assembled at their original planned cycle or displaced by  $\pm 1$ .

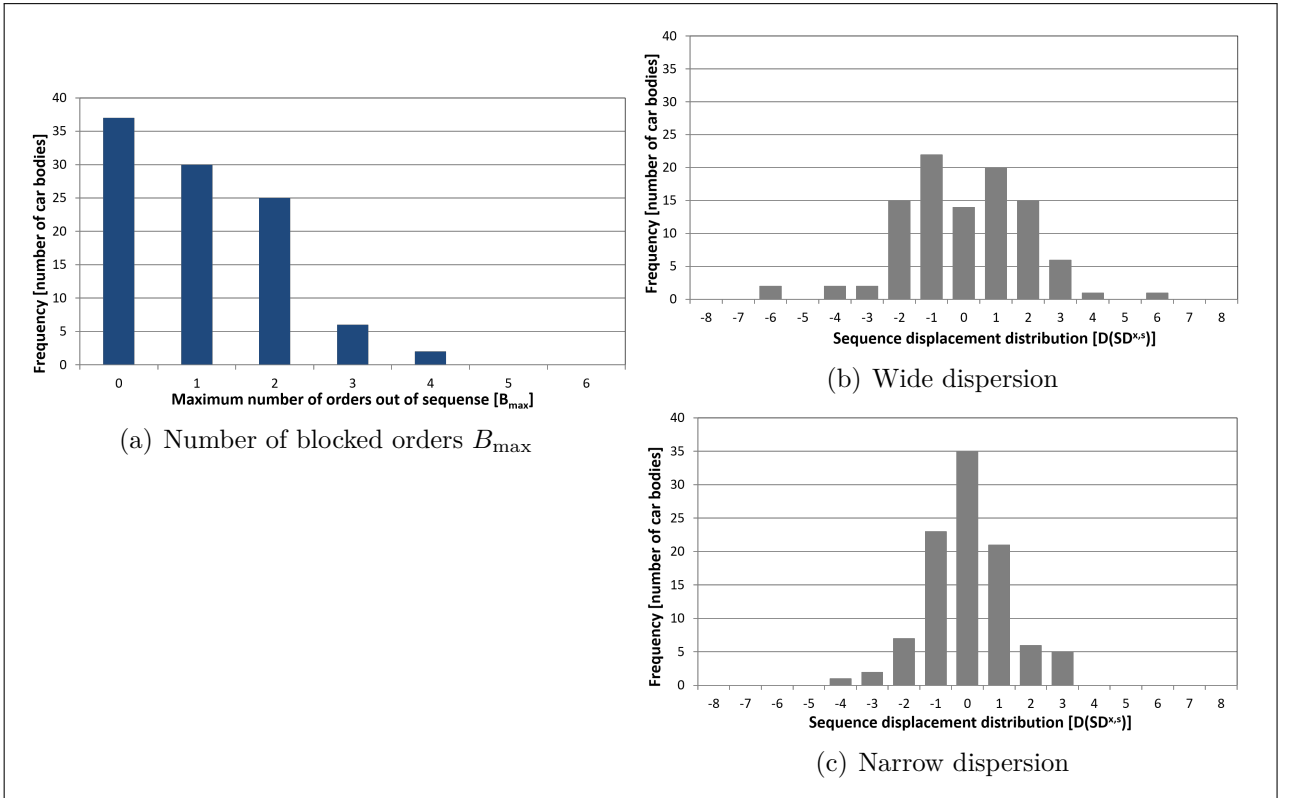


Figure 5: Presentation of  $B_{\max}$  with two possible characteristics of scrambling profiles  $D(SD_{\{1..C\}}^{x,s})$

#### 4.2. Characteristics of automotive production

The CBF is homogeneous because all orders move through the three main production steps. Nevertheless the  $D(SD_{\{1..C\}}^{x,s})$  of the production steps and processing times of individual orders differ due to rework, quality inspection and additional operations. This has an effect on the order's position in two successive sequences and causes sequence scrambling.

*Body Shop.* Car bodies consist of the front / rear compartment, the center floor, side panels, the roof, doors, the trunk lid as well as add on parts (Henriksson and Johansen, 2016). The fusion welding and joining are highly automated. At the start of the production the front compartment, the center floor and the rear compartment are produced simultaneously. Afterwards they are joined at the underbody assembly. From then on car bodies move sequentially from one work station to another (Spieckermann et al., 2000). This is usually the point where the car body gets an identity number and can be assigned to a customer order (Inman and Schmeling, 2003). It is also the first time where car bodies are in a specific sequence and therefore, stability can be measured. Some car bodies need additional production steps, resulting in divergent part routing. After attaching side panels and the roof, the car body moves to the final inspection and is transferred to reworking sections, if needed (Ceglarek et al., 1995). While a machine breakdown or blocking of a machine in a single line assembly has no effect on the sequence, different part routing results in scrambling. In Figure 6 the absolute distribution  $D(SD_{\{1...C\}}^{bx,0})$  of the body shop is displayed. It is right-skewed ( $E(x) = 0; Var(x) = 69.12; \gamma_m = 62.09$ ), the mass of the distribution is concentrated on the right of the figure. The shape of the distribution is caused by lead time variations. Some cars

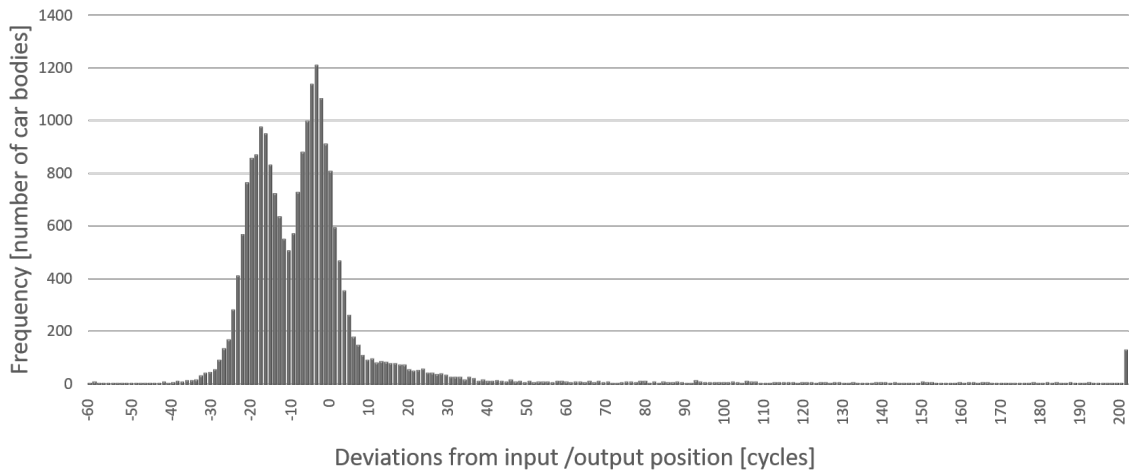


Figure 6: Scrambling at the body shop

need extra work cycles and are transferred to an additional production loop. These orders fall behind while others overtake. It results in the distinctive two peaks distribution. As the extra production loop consists only of a few work cycles, the two peaks are close to each other. Rework causes major sequence scrambling and moves the distribution to the right.



*Paint shop.* At the paint shop a multilayer coating is applied to the car body. The production steps usually comprise a pretreatment with applying substrate onto the car body, the primer and the primer surface, the base coat as well as the top coat. In between these steps there are cleaning, drying and baking sections (Spieckermann et al., 2007). At the end of the assembly line there are inspection and repair stations (Li, 2004). At some OEM's small batches from four up to six cars with the same color are entering the paint shop to optimize set-up times and decrease the loss of color while washing out the spray nozzles (Epping et al., 2004). However, emerging applying technologies reduce this effect, making batch sizing less important.  $D(SD_{\{1...C\}}^{px,pa})$  in Figure 7 displays the paint shop without batch sizing. It has a positive skew ( $E(x) = 0.12; Var(x) = 89.16; \gamma_m = 2.37$ ), the right tail is longer, i.e., it has more probability mass on the left than on the right. The values of  $SD_{\{1...C\}}^{px,pa}$  do not add up to zero due to the fact that two extreme outliers have been discarded from the sample.

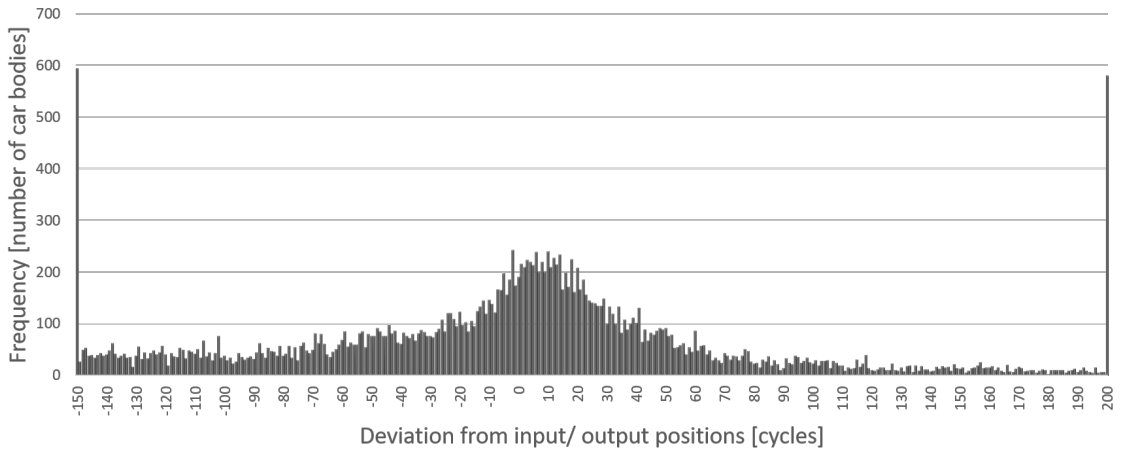


Figure 7: Scrambling at the paint shop

Investigations of the data basis reveal the following. Up to 60 percent of car bodies are getting a rework at spot repair stations or run through the manufacturing step of applying the top coat a second time. This effect moves the distribution to the right. In some cases a car body is scrapped, e.g., if the quality level of the topcoat is not achieved and cannot be reworked. The scrapped car body is removed from production process. The replenishment time to replace the order has a huge impact on the shape of the distribution. The substitute car body falls behind by many positions. Another effect on the shape of the distribution are differing lead times in color options. Specific paint finish such as individualized colors of top coats or polished piano lacquer lead to different throughput times. Quality inspections, such

as color matching, where individual car bodies are taken from the production process are an additional source for lateness (Arinez et al., 2010).

*Final assembly.* At the final assembly car bodies are moving along a transfer line. Interior and exterior trims as well as parts are assembled (Omar, 2011). Once the car body is released into the final assembly line it is very unlikely that scrambling occurs, since overtaking is at most points of the assembly line technically not possible. From the logistical point of view at this production stage scrambling is not permitted. JIS concepts are applied and a change in the sequence order will lead to an empty cycle or disproportionately high logistical expenditure (Heinecke et al., 2012). That is why  $D(SD_{\{1..c\}}^{0,fa})$  in Figure 8 is different to the once before. Instead of showing the scrambling of one production step it displays the  $SD_c^{0,fa}$ ; the sequence deviation of order  $c$  before the dispatching compared to the sequence original scheduled.

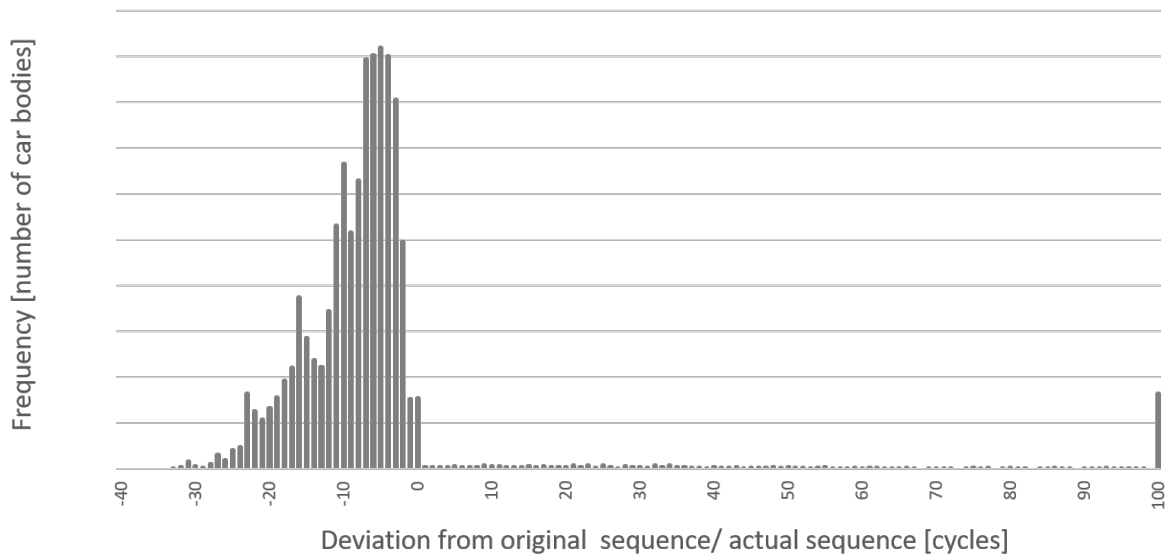


Figure 8: Scrambling at the final assembly

The typical shape of the distribution is caused by very few orders with a long delay and a large number of orders which are pulled forward by a few positions. There are two events that cause delay at the final assembly: firstly, the car body is missing, secondly, the order is blocked. The first effect occurs when the re-sequencing volume is low or scrambling in upstream processes exceeds a specific level. The second happens for different reasons. The act of blocking is independent of the physical location of the order. In the event of blocking the order is marked, proceeds through the current production step and is locked as soon as it is stored in the buffer. Only an active authorization enables the removal from storage.

Further information with the cause of change of the position is added to the blocked order. It facilitates the allocation of operating expenses to the responsible department and costs can directly be assigned to the divisions on the basis of services used. Different stakeholders are permitted to block orders. Upstream production departments, e.g., saddlery, axle assembly and engine production, usually supply JIS material. They start manufacturing after the freezing of the final assembly sequence. Detected missing or not working parts will lead to blocking of car bodies on short notice. Connected services, e.g., the quality or logistics department, detect quality related problems or operating errors occur, which causes a lock down if the part cannot be exchanged or replaced in rework. The pilot production center also affects the production process. New models which are at an early life cycle status are often accompanied by engineers at the final assembly. These car bodies are blocked and released at a scheduled time. The production control center intervenes actively in the succession of vehicles to ensure minimum number of violations of rules. If an order is blocked another car from the buffer is assembled instead to maintain the production throughput. The alternative car scrambles the original sequence and might induce sequencing rules.

## **5. Empirical study**

We outline the three main phases of the simulation study: the conception, the implementation and the analysis (Montevechi et al., 2007). The conception combines the objective definition, the data and the construction of the conceptual model. The implementation phase involves the development of the computer model and the operation of the simulation. Both phases include validation and verification steps.

### *5.1. Conception*

*Conceptual model and control strategies.* In the initial stage the simulation model reflects the production site of a German premium automotive manufacturer with a stabilized production setting. The plant consists of body shop, paint shop and final assembly with linear aligned buffers in between. Production steps and buffers are connected to each other by means of conveyor lines through which car bodies are handled on skids. The model is adapted towards a system with a shared buffer as illustrated in Figure 9. The retrieval strategy of the shared buffer is based on the dispatching policies of the paint shop and the final assembly, respectively. At the paint shop the car body released next is solely determined by the sequence number of

the original schedule. Every time an unpainted car enters the buffer the  $BFL_t^{up}$  is sorted in an ascending order based on the initially planned sequence number of the final assembly. As soon as the first station at the paint shop is free the first car body from that list is dispatched. At the final assembly this dispatching logic is enhanced by detent related information and sequencing rules in form of spacing restriction. Every time an unpainted car enters or a blocked is resolved the  $BFL_t^{up}$  is sorted in an ascending order based on the sequence number. Before a painted car body is released into the final assembly line it is checked whether or not the car on the first position is affected by an detent or whether a blocked order has been unblocked. Additionally, spacing restrictions are considered. If the car body carries any related information. The sequence of the already dispatched car bodies is taken into account. If a violation of spacing restriction occurs the car body is put on hold for one cycle and the car body with the next highest sequence number is checked.

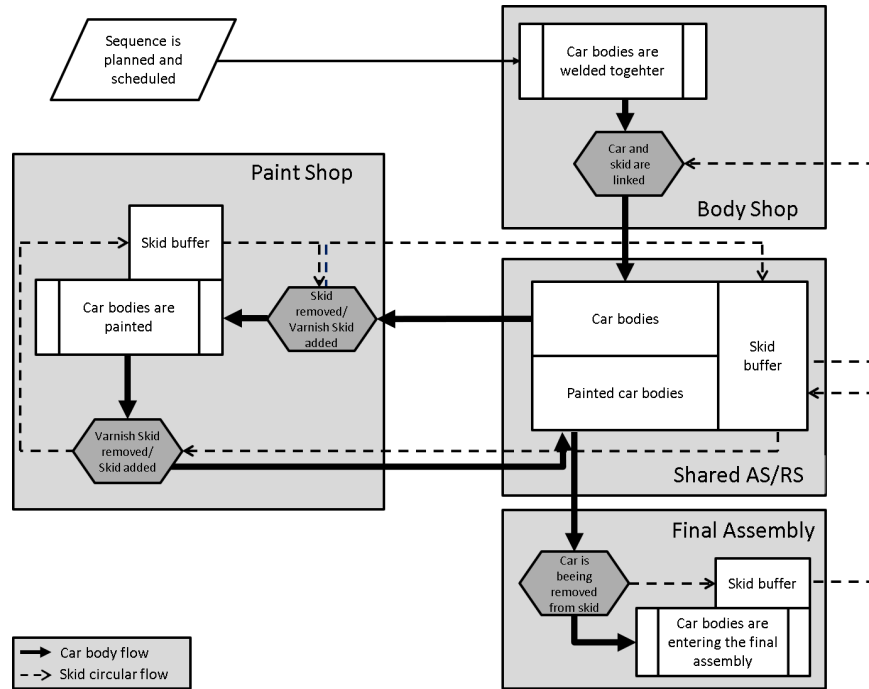


Figure 9: Flow chart of the conceptual model

In our study we focus on one skid type that supplies all production steps with car bodies. This means that internal processes within the production steps are not considered. The CBF and skid flow have a source to sink relation. After the body shop car bodies enter the buffer on skids. When transferred into the pretreatment process of the paint shop skids are released. After the painting process car bodies are consigned once again onto skids and are stored in the buffer. When cars are dispatched into the final assembly skids are getting vacant. In order

to ensure a smooth production flow sources (final assembly line and entrance of the paint shop) must always have the possibility to issue skids so that sinks (body shop and exit of the paint shop) are supplied with skids. To provide a smooth CBF and skid flow the following assumptions are made:

- Car bodies are delivered to the shared buffer during all three shifts per day (no blocking in the CBF due to a filled up buffer occurs).
- Car bodies are delivered to and painted car bodies retrieved from the paint body shop on time (no blocking or starving occurs).
- The final assembly line is supplied with painted car bodies on time and meets the planned throughput (no starvation due to the lack of painted bodies occurs).
- The stability level  $SL_\beta$  at the final assembly is  $\geq 98$  percent. This target level is set by the management and is also stated as reasonable in literature (Inman, 2003; Gusikhin et al., 2008; Müller et al., 2020).
- There are always sufficient skids to transport car bodies and painted bodies to or from the shared buffer.

*Optimal number of skids.* Determining the required amount of transportation devices is an important planning task of all closed production systems. The optimal number of skids prevents conveyor sections and production steps from blocking and avoids idle times. The initial number of skids is calculated by adding up the average WIP in movement on the conveyor lines, the maximum filling level of the shared buffer and half the filling of the two skid buffers. This gives a total sum of 240 skids. The simulation model is used to verify and optimize this number.

*Operating policy of the skid flow.* The control strategy of skids is based on trigger points. The minimum filling level of skid buffers at production steps define the trigger point at which a skid from a given source is requested. The maximum filling level defines trigger points at which a skid is delivered to a predefined sink. The shared buffer serves as both, a sink if all skid buffers are full or as a source, if all skid buffers are empty. The WIP on the conveyor lines counts as inventory of the receiving buffer. In order to minimize the number of empty runs and movements an optimum filling level for every buffer is defined:

- A skid buffer only serves as a sink and takes skids from a source when its filling level is dropping below the planned level.
- A skid buffer is used as a source and delivers skids to a requesting sink only when the planned filling level is exceeded.

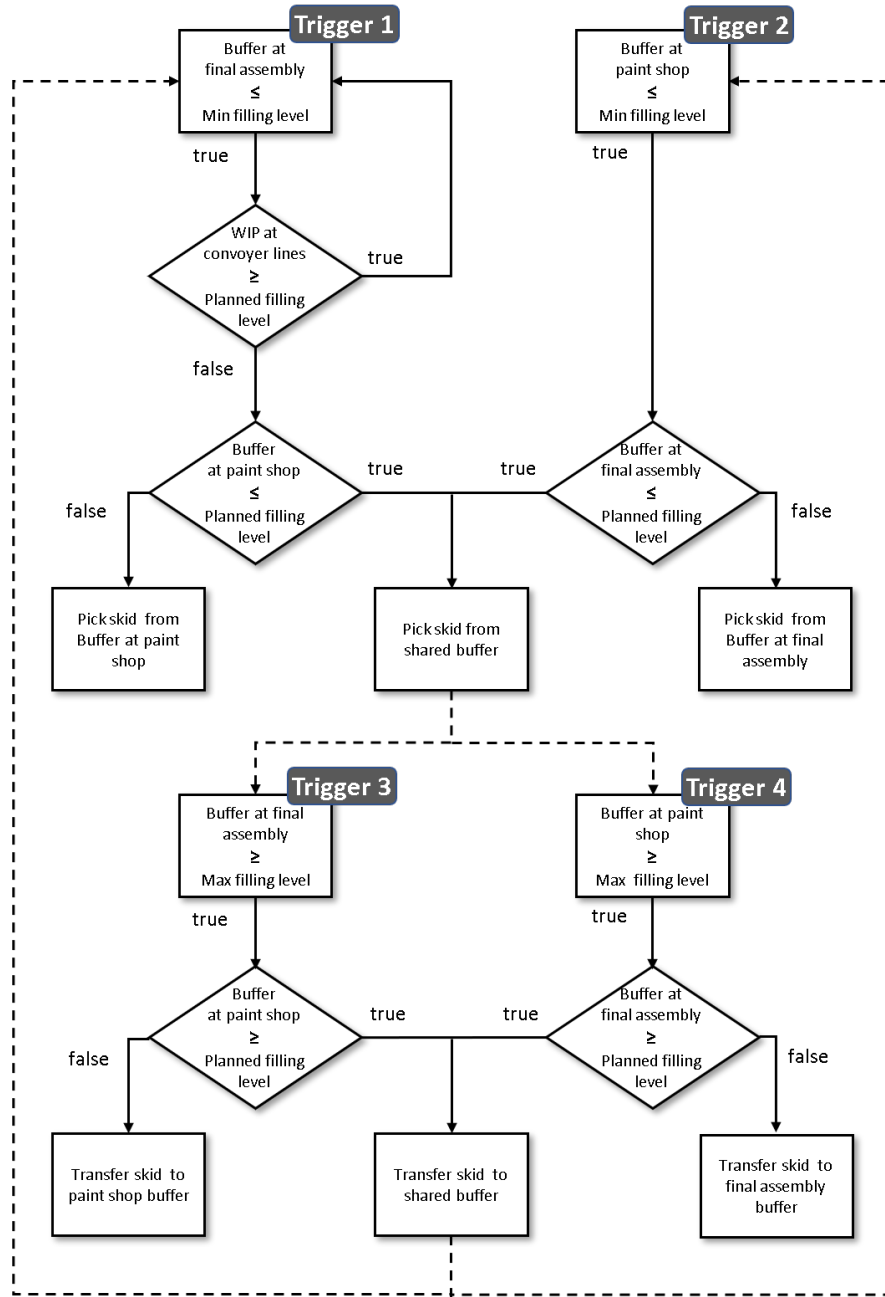


Figure 10: Flow chart of skid dispatching policy

The exact determination of the steering logic is displayed in Figure 10 and works as follows. Every time a skid enters or leaves the paint shop buffer it is checked whether or not the filling

level is below the minimum mark (trigger 1) or above the maximum mark (trigger 3). A skid is transferred from the paint shop buffer to the final assembly buffer if the filling level of the paint shop is above the planned level and the WIP on the conveyor lines is below the marked level. Otherwise a skid is requested from the shared buffer. If the buffer at the final assembly exceeds the maximum level the skid is transferred to the paint shop or, if that buffer is above the planned filling level, it is transferred to the shared buffer. The same control logic applies for the paint shop buffer (trigger 2 and 4). The simulation model is used to validate and optimize these planning parameters.

*Preparation of production data.* The applied data set is taken from a German OEM and serves as input for our simulation study. It comprises 80 production days with 20,000 manufactured orders. The production data includes the factory calendar, working schedules, idle times as well as the distribution of failures and downtime of the shops. Furthermore, it contains the following information for each order:  $SN_c^0$ ,  $SN_c^{bx}$ ,  $SN_c^{pa}$ ,  $SN_c^{px}$ ,  $SN_c^{fa}$ , time stamps at specific checkpoints along the production flow, the vehicle type, the body color, equipment features and relevant information for sequencing rules. In total there are over 20,000 vehicle orders enriched with 36 production-relevant information making it more than one million data entries. Orders with missing or incorrect information are removed from the data set. The descriptive analysis of the input data also includes the analyses of  $D(SD_{\{1..C\}}^{fa,O})$  based on car body types and styles as displayed in Figure 11.

## 5.2. Modeling approach

*Implementation.* One challenge of simulation approaches is to reduce the complexity of the manufacturing system to a suitable level and select appropriate input parameters and modeling assumptions (Law, 1991). Thereby the degree of detail plays an important role, it varies between the different steps. The body and paint shop are designed as black boxes and not mapped in detail. I.e., individual machines and stations at the production line are not displayed. The functionality of these steps is not modeled explicitly but the distribution of scrambling effects are embodied in the applied data. The functionality of the connecting conveyor lines between production steps and the steering logic of the shared buffer have a determining impact on the simulation result; they are therefore illustrated in detail.

The simulation model is implemented in Plant Simulation Version 12. Standard modules from Plant Simulation, from the automotive library of the Association of the German Auto-

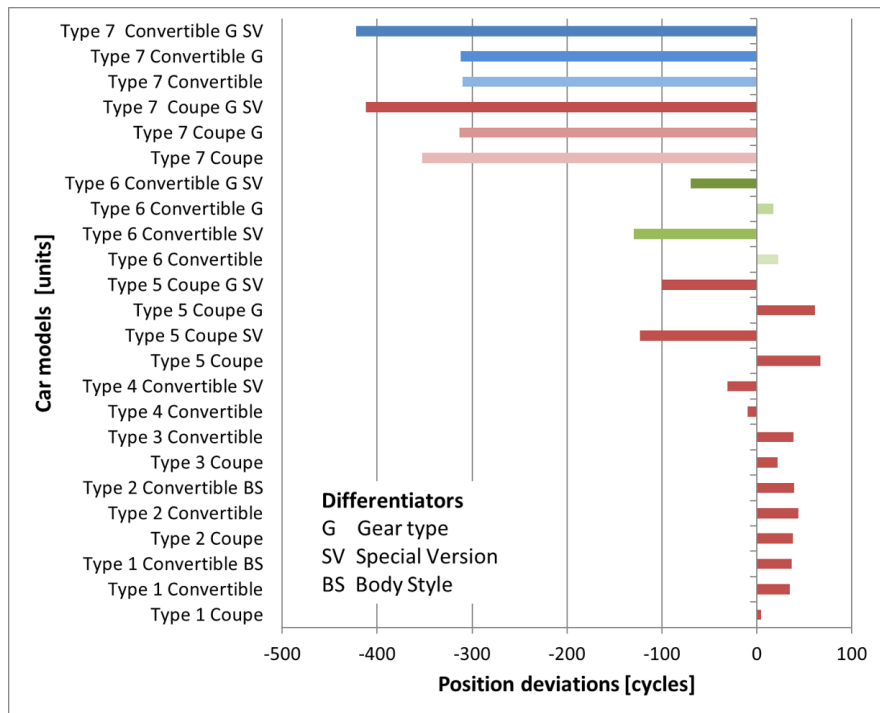


Figure 11: Position deviations based on car body types and styles

motive Industry (VDA) and user modules are employed for programming. The DeSequencer module from the VDA library is applied to depict the body shop and the paint shop. Based on the production data, it displays the earliness and lateness distribution of car bodies. The conveyor technique between production steps consists of simple connectors. The storage capacity of these conveyors is represented by the VDA module Space Buffer. Merging of skids and car bodies is done via the VDA module Assembly Station. The model has two sources. One creates orders, the other generates a predefined amount of skids at the beginning of the simulation. Orders are entities containing a set of information.

*Operational model.* The simulation is operated on a computer featuring an Intel(R) Core (TM) i5-6440HQ CPU @ 2.6 GHZ with 16 GB RAM running under windows 10 Pro 64 bit. Each simulation experiment consists of ten runs with a different set of random numbers. A warm-up phase of seven days is set to establish a steady state of operating conditions. The system's dynamic behavior during normal operation is displayed in Table 2. Data is acquired by observing the real-world production system within a period of one year. There is a slight over-capacity in the upstream production areas. This assumptions is also stated in literature (Pine, 2008). We presume that the the material supply of the body shop is unlimited, i.e., the first station never starves. Furthermore, the buffer behind the final assembly is infinitely



large. Thus, the final assembly cannot be blocked.

	Body shop exit	Paint shop entrance	Paint shop exit	Final assembly entrance
<b>Target output</b>	100%	100%	100%	100%
min	98,8%	98,2%	97,6%	100%
average	100,1%	100,7%	100,4%	100%
max	102,4%	104,7%	104,1%	100%

Table 2: Variability of the throughput

*Model validation.* Verification and validation steps combine the suitability concerning the conceptual model, the assurance that the model matches the real-world system and the credibility of the model (Brooks and Tobias, 1996). We use event validity as validation technique, since the output data can be compared to the performance of the real-world manufacturing system (Sargent, 2005). By rebuilding exact production preconditions it is possible to compare  $SL_\beta$  on daily average of the simulation model to real-world observations. Therefore  $BFL_t^p$  in the model is set to the equivalent capacity of the existing  $BFL_t^{up}$ . Data collection starts after the warm-up period of one week. The mean values of  $SL_\beta$  are as follows; simulation experiments 97.13 percent and real-world observations 96.65 percent. The systematic overestimation of  $SL_\beta$  within the simulation experiments result from the simplified dispatching rules at the final assembly. Only the most important sequencing rules are applied. It can be observed that the simulation data provides a similar profile as the real-world system. The results are displayed in Figure 12. The identical peaks verify the functionality of the simulation model.

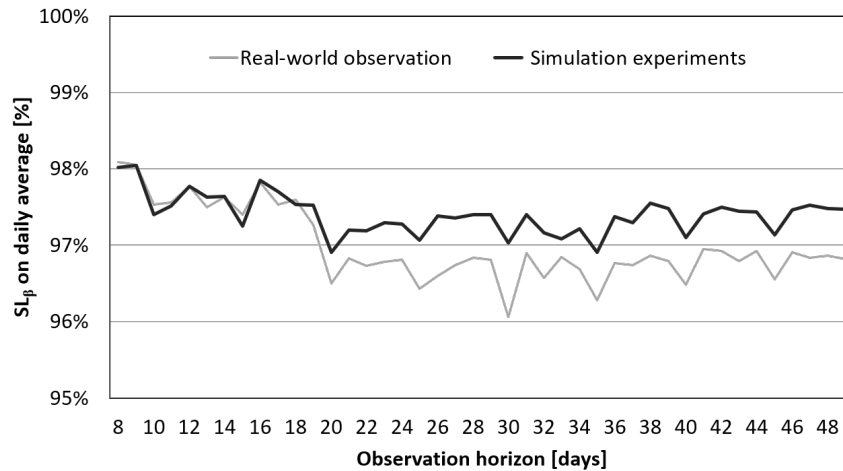


Figure 12: Comparison of  $SL_\beta$  within simulation experiments and real-world observations

## 6. Analysis and results

For each simulation run the  $BFL_t^{up}$ ,  $BFL_t^p$ , throughput as well as the CBF and skid flow on the conveyor lines are documented, examined and interpreted.  $SL_\beta$  is applied at the final assembly on a daily basis and plotted as a weekly or monthly time series.

### 6.1. Allocation of shared buffer capacity

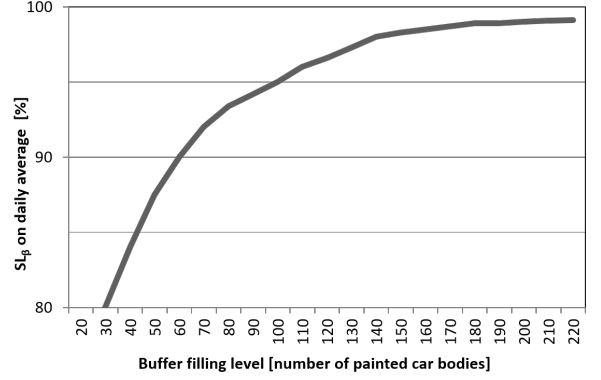
*Sequence stability.* In order to investigate dependencies of  $SL_\beta$  on  $BFL_t^{up}$  and  $BFL_t^p$  we run simulation experiments for different volumes. In the first run of the simulation experiments  $BFL_t^{up}$  is set to 1 and  $BFL_t^p$  is increased in steps of ten. Afterwards,  $BFL_t^{up}$  is set to 20, then 30 and finally 40. For each level  $BFL_t^p$  is increased in steps of ten. For each simulation run a range of 10 experiments with a different set of random numbers is conducted with a total sample size of 490 data entries. The table on the left-hand side of Figure 13 shows the results.  $SL_\beta$  is climbing steadily by raising  $BFL_t^{up}$  and  $BFL_t^p$ .  $SL_\beta \geq 98$  with the lowest capacity is reached by the combinations 150/ 1 ( $BFL_t^p$  /,  $BFL_t^u$ ), 140/ 20, 130/ 30 and 130/40. Reproducibility is expressed by confidence limits: with a probability of 99 percent the average  $SL_\beta$  for the combination 150/ 1 is within the interval of 0.978 to 0.981, 140/ 20 ( $K[0.983 \leq 0.984 \leq 0.986]$ ), 130/ 30 ( $K[0.978 \leq 0.980 \leq 0.982]$ ) and 130/40 ( $K[0.980 \leq 0.982 \leq 0.984]$ ).

The experiments reveal that there is only a minor positive effect on  $SL_\beta$  if  $BFL_t^{up}$  is raised. Since scrambling inside the paint shop is the strongest the positive effect of re-sequencing unpainted car bodies is diminished. In terms of stability it is more efficient to use the available buffer capacity with painted car bodies. Thus, for further experiments  $BFL_t^{up}$  is set to 1. Figure 13 right-hand side shows the concave course of  $SL_\beta$  on daily average as a function of the  $BFL_t^p$  (150/1). The  $SL_\beta$  target level of 98 percent is achieved with a re-sequencing volume of 2/3 of the daily throughput of the final assembly.

*Blocked orders.*  $B_{\max}$  describes the maximum amount of car bodies simultaneously out of position in the observation period. The value of  $B_{\max}$  corresponds to the number of places occupied by the material put aside and the advancement on sequencing positions. On the left-hand side of Figure 14 the frequency of  $B_{\max}$  is displayed. Two re-sequencing volumes are tested, one is equivalent to half and the other to two thirds of the daily throughput. The chart shows that in the case of a high level in over 92 percent of the observation period a

Number of Painted car bodies	Stability Level $SL_\beta$			
	1	20	30	40
110	0,9649	0,9685	0,9676	0,9694
120	0,9690	0,9714	0,9768	0,9787
130	0,9788	0,9744	0,9801	0,9822
140	0,9744	0,9842	0,9763	0,9822
150	0,9812	0,9848	0,9785	0,9832
160	0,9831	0,9869	0,9814	0,9858
170	0,9843	0,9873	0,9859	0,9858
180	0,9863	0,9873	0,9870	0,9859
190	0,9860	0,9894	0,9890	0,9880
200	0,9898	0,9903	0,9888	0,9911

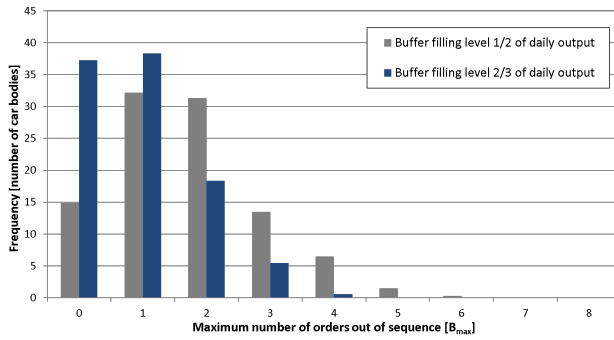
(a)  $SL_\beta$  as a function of the re-sequencing volume of unpainted cars and painted cars



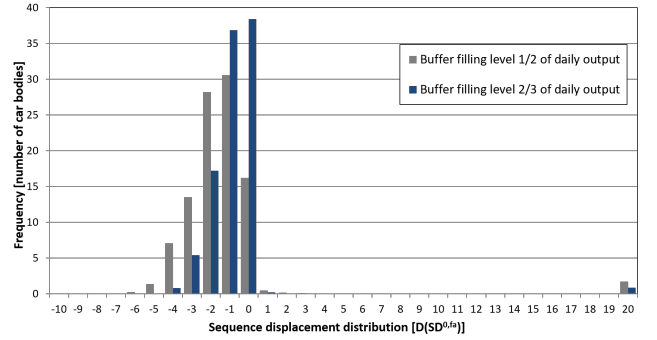
(b)  $SL_\beta$  as a function of the re-sequencing volume of painted cars

Figure 13:  $SL_\beta$  as a function of the re-sequencing volume of car bodies

maximum of two car bodies is blocked. I.e., all logistics areas at the final assembly must be designed in such a way that material for two car bodies can be stored.



(a) Maximum amount of orders simultaneously out of position  $B_{\max}$



(b) Scrambling profile  $D(SD_{\{1...C\}}^{0,fa})$

Figure 14: Sequence scrambling at the final assembly line as a function of the buffer filling level

The right-hand side of Figure 14 displays the distribution  $D(SD_{\{1...C\}}^{0,fa})$  of the final assembly compared to the sequence initially planned with two different  $BFL_t^p$ . It indicates if an order is assembled on time. A negative value has an effect on the supply of material as the supply chain is pulled forward. A positive value has an impact on the delivery performance. The majority of vehicles are scheduled at their initially planned position. Only very few car bodies fall behind causing the tail on the right-hand side of the distribution. Positive values are summed up at the amount of 20. If the re-sequencing volume is set to 2/3 of the daily volume in 73 percent of the observation period the car bodies are produced on time sequence position or are moved ahead by one position.

*Smoothing shift models.* Figure 15 displays filling levels during the course of five weeks. It shows typical characteristics of patterns with de-synchronized working schedules. The final assembly and paint shop operate in two and the body shop in three shifts. The night shift has only 60 percent of the production speed compared to the day shifts. During the day shifts  $BFL_t^{up}$  decreases and during the night the  $BFL_t^p$  is restocked. At the end of the third shift the buffer reaches  $BFL_{max}^{p,up}$ . Advantages of a shared buffer are revealed by comparing the required buffer capacity of a production system with two linear aligned buffers towards a system with a shared buffer. Linear aligned buffers should map the sum of  $BFL_{max}^{up}$  and  $BFL_{max}^p$ , whereas a shared buffer should map  $BFL_{max}^{p,up}$ . The comparison of the two single numbers to the value of the shared buffer in the observation period reveals the savings potential. These observations are displayed Figure 15. In this example capacity savings potential of a shared buffer is 6 percent.

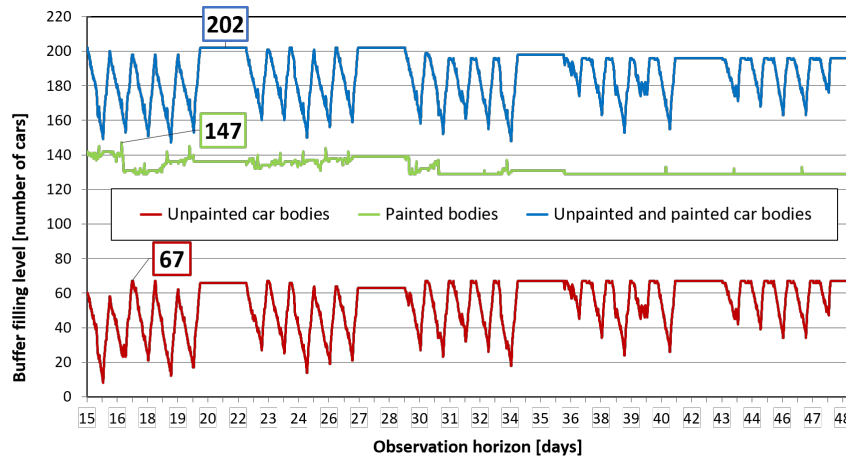


Figure 15: Filling pattern of the shared buffer ( $BFL_{max}^{p,up}$ : 202,  $BFL_{max}^{up}$ : 67,  $BFL_{max}^p$ : 147)

*Decoupling flow lines.* A series of experiments with a defined downtime of 30, 60, 180 minutes is conducted within an observation period of seven weeks and a total operating time of 70,560 minutes. The following assumptions are made. On average there is one downtime per week in the body shop and the paint shop. There is a maximum of two downtime per week or no downtime occurs. Downtime affects all three shifts and can affect both production steps simultaneously. The minimum  $BFL_t^p$  to maintain  $SL_\beta \geq 98$  percent is not undercut and a loss of throughput at the final assembly may occur. In addition, a downtime of a whole shift (480 minutes) at the paint shop is recorded. The downtime starts at the beginning of the morning shift. Figure 16 displays the filling pattern,  $BFL_{max}^{up,p}$ ,  $BFL_{max}^{up}$  and  $BFL_{max}^p$ .

Depending on the location of downtime  $BFL_t^{up}$  or  $BFL_t^p$  rises. The slightly pushing effect of upstream production steps indicated in Table 2 is fully exploited. Downtime of 30 minutes is compensated without lowering the throughput of the final assembly. At the 60 and 180 minutes downtime  $BFL_t^p$  drops to the minimum re-sequencing volume and throughput losses of the final assembly occur as displayed in Figure 16.  $BFL_t^p$  or  $BFL_t^p$  recovers temporarily due to downtime in the body shop or paint shop, respectively.

Compared to the sum of two separate buffers, a shared buffer generates significant capacity savings. In a downtime scenario with 30 minutes the  $BFL_{max}^{up,p}$  is 187 and the  $BFL_{max}^{up}$  56 and  $BFL_{max}^p$  151. Thus, to map the buffer capacity in a system with two separate buffers a total capacity of 207 units is required. The employment of a shared buffer reduces the required total capacity by 11 percent. With downtime scenarios of 60 and 180 minutes the savings are 8 percent and 10 percent.

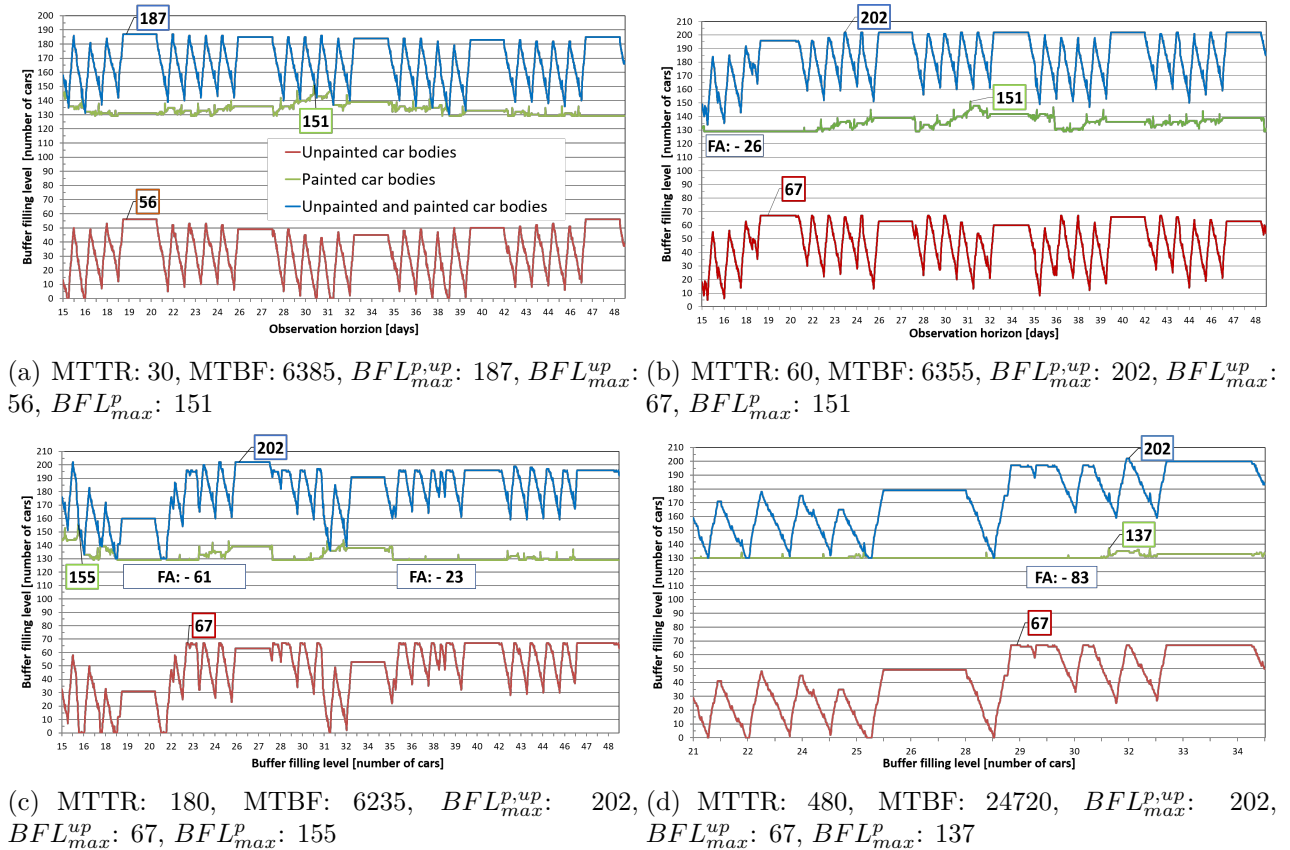


Figure 16: Buffer filling level ( $BFL_{max}^{p,up}$ ) with different mean time to repair (MTTR) and mean time between failures (MTBF) in minutes at the body and paint shop

## 7. Managerial insights and recommendations

Automotive production sites have to cope with the ongoing trend of increasing product variety and outsourcing strategies. In order to deal with the resulting tasks in the production process automotive producers transform their existing plants to SPSs. Core of this concept is the sequence of car bodies which is determined several days before the start of production and the material requirement forecast that derives from it. To exploit the advantages of such systems a high and constant level of stability in the flow of material and parts is required. Reasons of sequence scrambling in the process are widespread. An analysis of each production step reveals insights on sources of sequence scrambling. The distribution of the body shop is mainly shaped by different part routing, some car bodies fall behind while others overtake. This is contrary to the paint shop where sequence scrambling is primarily caused by rework and repair loops. Characteristically up to two third of car bodies are getting spot repair or run through the manufacturing step of applying the topcoat a second time. Furthermore, the replenishment time for scrapped car bodies lead to long delays. Scrambling at the final assembly is induced by the production control in order to comply with sequencing rules. Buffer capacity is required to diminish scrambling and fulfill several functions. Firstly, buffer decouple the main production steps body shop, paint shop and final assembly, avoid blocking and starving and therefore assure a stable production rate. Secondly, they enable different cycle times and shift models of production steps. Thirdly, an amount of car bodies are stored to compensate scrambling effects and to enable re-sequencing. And fourthly, buffer facilitate the storage of blocked car bodies that can not be dispatched at their scheduled position. In real-world manufacturing systems two separate buffers, one between the body and paint shop and one between the paint shop and final assembly, execute the required functions.

We conduct an empirical study with a German OEM and show that a shared buffer covers all buffer functions of an SPS. The stability level can be leveraged significantly by raising the sequencing volume, but this effect diminishes with additional sequencer volume. In the case study the recommended stability level of 98 percent is achieved with storing painted car bodies of an amount of approximately 2/3 of the daily output. The additional benefit of allocating unpainted car bodies for re-sequencing is marginal, as the sequence scrambling of the paint shop outweigh any positive effects.

Major benefits of a shared buffer reveal a series of experiments of differing processing

speeds and downtime in the body and paint shop. The initial ratio of unpainted and painted car bodies changes. If the body shop is blocked, the ratio shifts towards painted car bodies and vice versa. The slightly pushing effect of upstream production steps is fully exploited. While maintaining the same performance buffer capacity savings of up to 11 percent can be achieved compared to a production system with two separate buffers. The new production flow along with the increased volatility of the ratio of unpainted and painted car bodies necessitate an optimal number of skids and a performing operating policy. We develop, implement and verify control strategies which can easily be applied in practice.

From a practical point of view, this paper offers production system designers a methodology for selecting an optimal filling level of a shared buffer and implementing a steering logic. Further developments with the intention of using the simulation model as a decision support system in day-to-day business is highly recommended. With some extensions and adjustments it can be used to forecast real-world manufacturing scenarios. It enables the production control department to continuously examine and evaluate system behavior in the real-world manufacturing system by adjusting the model input parameters, such as model mix, cycle time, shift time or operating logic.

## **8. Conclusions and further research**

This paper addresses the question if a shared buffer within a multi section production line meets the requirements of SPSs in the automotive assembly. The potential stability level of an SPS with a shared buffer can be revealed with a DES simulation and an appropriate data set. The research questions are answered by analyzing the simulation results of a case study with a German premium car manufacturer. RQ1 is clearly answered by observing the stability layer plots of the final assembly. It shows the stability level as a function of the BFL of painted car bodies. While at lower BFLs the stability level is very reactive and a little increase of buffer capacity causes a significant enhancement, reaching a certain BFL results in modest improvement. In order to expose the effect of differing processing speeds and downtime on the filling level of the shared buffer (RQ2) a series of experiments are conducted. The ratio of painted and unpainted car bodies shifts according to the location of the downtime. It shows the flexible adjustment of the filling level and reveals capacity savings of up to 11 percent compared to a system with two linear aligned buffers. A shared buffer changes the

production flow as all car bodies pass the buffer twice. This leads to the question which production control policies are required (RQ3). We apply and optimize a control strategy for a steady flow and supply of skids.

In summary, the simulation study approves that a shared buffer facilitates all required buffer functions of an SPS. While this study makes significant theoretical and practical contributions, it has limitations that offers several opportunities for future research. The implementation of a shared AS/RS buffer is costly and causes a major change in the production setting. In existing production sites linear aligned buffers are already integrated into the production flow. Future contributions could address the economic comparison of linear aligned and a shared buffer as well as the amortization of the latter. The flexibility of the shared buffer can be further investigated by integrating countermeasures in specific production lines after downtime. A supplementary working shift in the body shop does not necessarily constrain an additional shift in the paint shop and contrariwise. This might increase the flexibility and productivity of the production site. Furthermore, new control strategies to re-adjust the ratio of unpainted and painted car bodies in the shared buffer, e.g., after a downtime, need to be determined and verified. The DES model provides possibilities for further extensions and investigations of what-if scenarios. To reduce complexity of the simulation model different abstraction levels are selected. The body and paint shop could be displayed in detail to analyze the scrambling sources in depth. Fundamental changes in the production setting or distribution of orders, i.e., the ramp-up of a new car model, could be another investigation scenario. Another possibility for further research is the analyzing of specific scheduling policies, such as shifting the order penetration point from the body shop towards successive production steps. Moreover, to reduce buffer capacity a virtual re-sequencing strategy along with reducing the variety of options could be taken into account. To the knowledge of the authors there is no study on how to evaluate an optimal stability level within a production process. To determine the optimal level methodically the trade-off between maintaining sequence stability and adherence of control strategies, e.g., dispatching rules, must be further investigated. Therefore the effect of sequence scrambling on additional logistic handling costs and the neglect of control strategies on costs of worker allocation at the final assembly must be balanced. Another trade-off in this context arises considering blocking orders due to missing parts or provoking subsequent assembling in rework sections after the final assembly.



## **9. Acknowledgements**

The case study was conducted with the German Premium car manufacturer Dr. Ing. h.c. F. Porsche AG. The findings of the simulation study were used within the design process of the shared buffer at the production site in Stuttgart. Meanwhile the results achieved are confirmed by the operating system.

We would like to thank the Dr. Ing. h.c. F. Porsche AG for the kind cooperation and their supply of data.

## References

- Alfieri, A., Matta, A., 2012. Mathematical programming formulations for approximate simulation of multistage production systems. *European Journal of Operational Research* 219, 773–783.
- Alszer, S., Krystek, J., Bysko, S., 2017. Simulation and virtual commissioning for intelligent buffer control system – case study, in: 2017 2nd International Conference on Robotics and Automation Engineering (ICRAE 2017): December 29-31, 2017, Shanghai, China, IEEE, Piscataway, NJ. pp. 207–211.
- Arinez, J., Biller, S., Meerkov, S.M., Zhang, L., 2010. Quality/quantity improvement in an automotive paint shop: A case study. *IEEE Transactions on Automation Science and Engineering* 7, 755–761.
- Banks, J., 1998. Principles of simulation, in: Banks, J. (Ed.), *Handbook of simulation: Principles, methodology, advances, applications, and practice*. Wiley and Co-published by Engineering & Management Press, New York and S.I., pp. 3–30.
- Berkley, B.J., 1992. A review of the kanban production control research literature. *Production and Operations Management* 1, 393–411.
- Boysen, N., Emde, S., Hoeck, M., Kauderer, M., 2015. Part logistics in the automotive industry: Decision problems, literature review and research agenda. *European Journal of Operational Research* 242, 107–120.
- Boysen, N., Fliedner, M., Scholl, A., 2008. Assembly line balancing: Which model to use when? *International Journal of Production Economics* 111, 509–528.
- Boysen, N., Golle, U., Rothlauf, F., 2011. The car resequencing problem with pull-off tables. *Business Research* 4, 276–292.
- Boysen, N., Scholl, A., Wopperer, N., 2012. Resequencing of mixed-model assembly lines: Survey and research agenda. *European Journal of Operational Research* 216, 594–604.
- Boysen, N., Zenker, M., 2013. A decomposition approach for the car resequencing problem with selectivity banks. *Computers & Operations Research* 40, 98–108.
- Brooks, R., Tobias, A., 1996. Choosing the best model: Level of detail, complexity, and model performance. *Mathematical and Computer Modelling* 24, 1–14.
- Burman, M., Gershwin, S.B., Suyematsu, C., 1998. Hewlett-Packard uses operations research to improve the design of a printer production line. *Interfaces* 28, 24–36.
- Buzacott, J.A., 1967. Automatic transfer lines with buffer stocks. *International Journal of Production Research* 5, 183–200.
- Buzacott, J.A., Yao, D.D., 1986. Flexible manufacturing systems: A review of analytical models. *Management Science* 32, 890–905.
- Cedillo-Campos, M.G., Morones Ruelas, D., Lizarraga-Lizarraga, G., Gonzalez-Feliu, J., Garza-Reyes, J.A., 2017. Decision policy scenarios for just-in-sequence (JIS) deliveries. *Journal of Industrial Engineering and Management* 10, 581.
- Ceglarek, D., Shi, J., et al., 1995. Dimensional variation reduction for automotive body assembly. *Manufacturing Review* 8.
- Choi, W., Shin, H., 1997. A real-time sequence control system for the level production of the automobile assembly line. *Computers & Industrial Engineering* 33, 769–772.
- Conway, R., Maxwell, W., McClain, J.O., Thomas, L.J., 1988. The role of work-in-process inventory in serial production lines. *Operations Research* 36, 228–241.
- Demir, L., Tunali, S., Eliyi, D.T., 2014. The state of the art on buffer allocation problem: A comprehensive survey. *Journal of Intelligent Manufacturing* 25, 371–392.
- Ding, F.Y., Sun, H., 2004. Sequence alteration and restoration related to sequenced parts delivery on an

- automobile mixed-model assembly line with multiple departments. *International Journal of Production Research* 42, 1525–1543.
- Dössel, K.F., 2008. In-plant repairs, in: Streitberger, H.J., Dössel, K.F. (Eds.), *Automotive paints and coatings*. 2. ed.. John Wiley & Sons, pp. 377–380.
- Enginarlar, E., Li, J., Meerkov, S.M., 2005. How lean can lean buffers be? *IIE Transactions* 37, 333–342.
- Epping, T., Hochstättler, W., Oertel, P., 2004. Complexity results on a paint shop problem. *Discrete Applied Mathematics* 136, 217–226.
- Fisher, M.L., Ittner, C.D., 1999. The impact of product variety on automobile assembly operations: Empirical evidence and simulation analysis. *Management Science* 45, 771–786.
- Fournier, X., Agard, B., 2007. Improvement of earliness and lateness by postponement on an automotive production line. *International Journal of Flexible Manufacturing Systems* 19, 107–121.
- Gershwin, S.B., Schick, I.C., 1983. Modeling and analysis of three-stage transfer lines with unreliable machines and finite buffers. *Operations Research* 1983, 354–380.
- Graves, R.J., Konopka, J.M., Milne, R.J., 2007. Literature review of material flow control mechanisms. *Production Planning & Control* 6, 395–403.
- Gstettner, S., Kuhn, H., 1996. Analysis of production control systems kanban and conwip. *International Journal of Production Research* 34, 3253–3273.
- Gunasekaran, A., Reichhart, A., Holweg, M., 2007. Creating the customer-responsive supply chain: A reconciliation of concepts. *International Journal of Operations & Production Management* 27, 1144–1172.
- Günther, M.T., 2017. *Produktionssteuerung nach dem Perlenketten-Prinzip am Beispiel der Automobilfertigung*. Friedrich-Schiller-Universität Jena.
- Gusikhin, O., Caprihan, R., Stecke, K.E., 2008. Least in-sequence probability heuristic for mixed-volume production lines. *International Journal of Production Research* 46, 647–673.
- Heinecke, G., Köber, J., Lepratti, R., Lamparter, S., Kunz, A., 2012. Event-driven order rescheduling model for just-in-sequence deliveries to a mixed-model assembly line, in: *IFIP International Conference on Advances in Production Management Systems*, Springer. pp. 326–333.
- Henriksson, F., Johansen, K., 2016. An outlook on multi material body solutions in the automotive industry—possibilities and manufacturing challenges, in: *SAE 2016 World Congress and Exhibition*, Society of Automotive Engineers.
- Herlyn, W., 2012. *PPS im Automobilbau: Produktionsprogrammplanung und -steuerung von Fahrzeugen und Aggregaten*. 1. Aufl. ed., Carl Hanser Fachbuchverlag, s.l.
- Hoffmann, C.A., 2018. *Methodik zur Steuerung modularer Produktbaukästen*. Springer Fachmedien Wiesbaden, Wiesbaden.
- Holweg, M., Pil, F.K., et al., 2005. The second century: reconnecting customer and value chain through build-to-order moving beyond mass and lean in the auto industry. *MIT Press Books* 1.
- Houshyar, A., 1991. A heuristic for determination of optimal capacity of central storage. *Computers & Industrial Engineering* 21, 447–451.
- Hurley, S.F., 1996. A practical heuristic for effective buffer management. *International Journal of Operations & Production Management* 16, 89–101.
- Inman, R.R., 2003. ASRS sizing for recreating automotive assembly sequences. *International Journal of Production Research* 41, 847–863.
- Inman, R.R., Bulfin, R.L., 1991. Sequencing JIT mixed-model assembly lines. *Management Science* 37, 901–904.
- Inman, R.R., Schmeling, D.M., 2003. Algorithm for agile assembling-to-order in the automotive industry.

- International Journal of Production Research 41, 3831–3848.
- Ito, K., Sallee, J.M., 2018. The economics of attribute-based regulation: Theory and evidence from fuel economy standards. *Review of Economics and Statistics* 100, 319–336.
- Junior, M., Filho, M., 2010. Variations of the kanban system: Literature review and classification. *International Journal of Production Economics* 125, 13–21.
- Kortmann, S., Gelhard, C., Zimmermann, C., Piller, F.T., 2014. Linking strategic flexibility and operational efficiency: The mediating role of ambidextrous operational capabilities. *Journal of Operations Management* 32, 475–490.
- Krcal, H.C., 2008. Strategische Implikationen einer geringen Fertigungstiefe für die Automobilindustrie. *Schmalenbachs Zeitschrift für betriebswirtschaftliche Forschung* 60, 778–808.
- Kuhnert, F., Stürmer, C., Koster, A., 2018. Five trends transforming the automotive industry. URL: <https://eu-smartcities.eu/sites/default/files/2018-03.pdf>.
- Lahmar, M., Ergan, H., Benjaafar, S., 2003. Resequencing and feature assignment on an automated assembly line. *IEEE Transactions on Robotics and Automation* 19, 89–102.
- Law, A.M., 1991. Simulation model's level of detail determines effectiveness. *Industrial Engineering* 23, 16–18.
- Lehmann, M., Kuhn, H., 2019. Modeling and analyzing sequence stability in flexible automotive production systems. *Flexible Services and Manufacturing Journal* 192, 349.
- Li, J., 2004. Throughput analysis in automotive paint shops: A case study. *IEEE Transactions on Automation Science and Engineering* 1, 90–98.
- Li, J., Blumenfeld, E.D., Huang, N., Alden, M.J., 2009. Throughput analysis of production systems: Recent advances and future topics. *International Journal of Production Research* 47, 3823–3851.
- Lim, A., Xu, Z., 2009. Searching optimal resequencing and feature assignment on an automated assembly line. *Journal of the Operational Research Society* 60, 361–371.
- Macgregor Smith, J., Cruz, F., 2005. The buffer allocation problem for general finite buffer queueing networks. *IIE Transactions* 37, 343–365.
- Mahadevan, B., Narendran, T.T., 1993. Buffer levels and choice of material handling device in flexible manufacturing systems. *European Journal of Operational Research* 69, 166–176.
- Matta, A., Runchina, M., Tolio, T., 2006. Automated flow lines with shared buffer, in: Liberopoulos, G., Papadopoulos, C.T., Tan, B., Smith, J.M., Gershwin, S.B. (Eds.), *Stochastic Modeling of Manufacturing Systems*. Springer-Verlag, s.l., pp. 99–120.
- Meissner, S., 2010. Controlling just-in-sequence flow-production. *Logistics Research* 2, 45–53.
- Meyr, H., 2004. Supply chain planning in the german automotive industry. *OR Spectrum* 26.
- Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., Chryssolouris, G., 2010. Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach. *CIRP Journal of Manufacturing Science and Technology* 2, 81–91.
- Montevechi, J.A.B., Ferreira de Pinho, A., Fabiano, L., Marins, F., 2007. Application of design of experiments on the simulation of a process in an automotive industry., in: *Proceedings of the 2007 Winter Simulation Conference*, Washington, DC, USA., pp. 1601–1609.
- Morrison, K.R., 1991. Animation - a new dimension in computer simulation of automotive assembly processes. *Computers & Industrial Engineering* 21, 547–551.
- Müller, M., Burges, U., 2020. Herausforderungen bei der Dimensionierung eines zentralen Entkopplungsmoduls in der Variantenfließfertigung und Darstellung eines selbstregulierenden Kreislaufsystems für Transportmittel., in: Mayer, G., Pöge, C., Spieckermann, S., Wenzel, S. (Eds.), *Ablaufsimulation in der Automobilindustrie*. Springer Vieweg. in Springer Fachmedien Wiesbaden GmbH, pp. 217–229.

- Müller, M., Kuhn, H., 2020. Analyzing a centralized buffer in automotive production plants - a simulation study, in: Xu, X., Dessouky, M.I., Zhong, R.Y. (Eds.), 49th International Conference on Computers and Industrial Engineering 2019 (CIE49), Computers and Industrial Engineering. Curran Associates. pp. 455–463.
- Müller, M., Lehmann, M., Kuhn, H., 2020. Measuring sequence stability in automotive production lines. *International Journal of Production Research* 0, 1–21. doi:10.1080/00207543.2020.1790685.
- Omar, M.A., 2011. *The Automotive Body Manufacturing Systems and Processes*. John Wiley & Sons, Ltd, Chichester, UK.
- Papadopoulos, H.T., Heavey, C., 1996. Queueing theory in manufacturing systems analysis and design: A classification of models for production and transfer lines. *European Journal of Operational Research* 92, 1–27.
- Papadopoulos, H.T., O’Kelly, M., 1993. Exact analysis of production lines with no intermediate buffers. *European Journal of Operational Research* 65, 118–137.
- Pine, B.J., 2008. *Mass customization: The new frontier in business competition*. Harvard Business School Press, Boston, Mass.
- Robinson, L.W., McClain, J.O., Thomas, L.J., 1990. The good, the bad and the ugly: Quality on an assembly line. *International Journal of Production Research* 28, 963–980.
- Rybicka, J., Tiwari, A., Enticott, S., 2016. Testing a flexible manufacturing system facility production capacity through discrete event simulation: automotive case study. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering* 10, 690–694.
- Salvador, F., Rungtusanatham, M., Akpinar, A., Forza, C., 2008. Strategic capabilities for mass customization: Theoretical synthesis and empirical evidence. *Academy of Management Proceedings* 2008, 1–6.
- Sargent, R.G., 2005. Verification and validation of simulation models, in: *Proceedings of the 37th conference on Winter simulation, Winter Simulation Conference*. pp. 130–143.
- Sawyer, C.A., 1994. In-line sequencing: how it’s done at wixom. *Automotive Industries* 174, 41.
- Singholi, A., 2015. Impact of manufacturing flexibility and pallets on buffer delay in flexible manufacturing systems. *International Journal of Engineering Management and Economics* 5, 308.
- Sörensen, K., Gerrit K. Janssens, 2001. Buffer allocation and required availability in a transfer line with unreliable machines. *International Journal of Production Economics* 74, 163–173.
- Spieckermann, S., Gutenschwager, K., Heinzl, H., Voß, S., 2000. Simulation-based optimization in the automotive industry – a case study on body shop design. *Simulation* 75, 276–286.
- Spieckermann, S., Gutenschwager, K., Voß, S., 2007. A sequential ordering problem in automotive paint shops. *International Journal of Production Research* 42, 1865–1878.
- Tempelmeier, H., Kuhn, H., 1993. *Flexible manufacturing systems: Decision support for design and operation*. A Wiley-Interscience publication, Wiley, New York.
- Tu, Q., Vonderembse, M.A., Ragu-Nathan, T.S., Ragu-Nathan, B., 2004. Measuring modularity-based manufacturing practices and their impact on mass customization capability: A customer-driven perspective. *Decision Sciences* 35, 147–168.
- Voller, G., Kistler, M., 1997. New AS/RS facility at Ford Cologne. *Automotive Technology International* , 173.
- Volling, T., 2009. *Auftragsbezogene Planung bei variantenreicher Serienproduktion: Eine Untersuchung mit Fallstudien aus der Automobilindustrie*. Gabler Edition Wissenschaft Produktion und Logistik. 1. ed., Gabler Verlag / GWV Fachverlage GmbH Wiesbaden, Wiesbaden.
- Walcher, D., Piller, F.T., 2012. *The customization 500: an international benchmark study on mass customiza-*

- tion and personalization in consumer e-commerce. ICON Group International.
- Weiss, S., Schwarz, J.A., Stolletz, R., 2018. The buffer allocation problem in production lines: Formulations, solution methods, and instances. *IISE Transactions* 51, 456–485.
- Weyer, M., 2002. Das Produktionssteuerungskonzept Perlenkette und dessen Kennzahlensystem, Univ., Diss. Helmesverlag, Karlsruhe.
- Wijngaard, J., 1979. The effect of interstage buffer storage on the output of two unreliable production units in series, with different production rates. *AIIE transactions* 11, 42–47.
- Womack, J.P., Jones, D.T., Roos, D., 2006. The machine that changed the world: how Japan's secret weapon in the global auto wars will revolutionize Western industry. Harper Perennial, New York, NY.
- Zeigler, B.P., Praehofer, H., Kim, T.G., 2010. Theory of modeling and simulation: Integrating discrete event and continuous complex dynamic systems. 2. ed., Academic Press, Amsterdam.
- Zhang, M., Guo, H., Huo, B., Zhao, X., Huang, J., 2019. Linking supply chain quality integration with mass customization and product modularity. *International Journal of Production Economics* 207, 227–235.
- Zhang, M., Matta, A., 2020. Models and algorithms for throughput improvement problem of serial production lines via downtime reduction. *IISE Transactions* 52, 1189–1203.

# Assembly line feeding concepts and supermarket allocation in automotive production

Marcel Lehmann, Mareike Müller, Heinrich Kuhn

---

## Abstract

The current trend towards a greater extend of models as well as variants leads to the development of more flexible production layouts in the automotive industry. This causes increasing logistical effort to supply the assembly with parts efficiently and results in an adaption of logistics concepts. Therefore, so called supermarkets are installed to feed the assembly areas just-in-sequence. One crucial planning task linked to the supermarket approach is the efficient allocation of parts to logistics areas and the integration of these areas inside the manufacturing facility. Since space is scarce and many potential logistics areas are reserved for assembly lines, there are several restrictions. Additionally, there are different material specific assumptions and planning premises especially in an environment where a supermarket supplies multiple assembly lines. This paper provides a description of the supermarket concept in multi-line automotive manufacturing plants and the related location planning problem. A mathematical description in form of a Mixed Integer Programming is presented to solve the proposed problem. The applicability is shown in a computational study based on a real-world data set provided by a German premium car manufacturer. We show the efficiency of a mathematical planning approach for supermarket allocation including the corresponding transportation costs to the final assembly line. The model provided generates cost savings of nineteen percent compared to the solution applied manually in the real-world environment.

*Keywords:* Mixed-model assembly lines, Automotive industry, JIS delivery, Supermarket allocation, Mixed Integer Programming (MIP), Generalized assignment Problem (GAP), Empirical study

---

## 1. Introduction

The successful development of the premium automotive industry during the last decades is based on satisfying the demand of their customers for highly individualized cars. The rising number of models as well as variants increases the flow of parts and material handling. This augments the logistics systems and its importance compared to the rest of the production process (Battini et al., 2013; Boysen et al., 2015). The effect is reinforced by the reduction of the in-house production rate and the development of new concepts to enhance the flexibility, e.g., modular production systems (Krcal, 2008; Kern et al., 2017; Hottenrott and Grunow, 2019). Furthermore, concepts of Logistics 4.0 denote a fundamental change in value creating systems causing new challenges in in-house logistics (Strandhagen et al., 2017). Due to limited space at the assembly line the existing logistics systems cannot be scaled economically to the required level of capacity and flexibility. These trends make the part logistics one of the most demanding operative tasks in automotive production and therefore to a current topic in research (Boysen and Emde, 2014; Delfmann et al., 2018). Inspired by the Toyota Production System just-in-sequence (JIS) delivery of parts to the production line are applied to meet the requirements (Inman, 2003; Ohno, 2013). These types of logistics processes are part of the line feeding process, which supplies parts and components from a central warehouse to work stations of the assembly line (Battini et al., 2009). Line feeding policies are mainly classified into line side stocking, kitting, sequencing, kanban-based or hybrid approaches (Battini et al., 2009; Faccio et al., 2015; Schmid et al., 2018). Selecting the most suitable policy is an important planning task and is heavily responsible for the performance of the assembly line (Battini et al., 2009; Boysen et al., 2015). JIS related systems have to be well planned since they cause a high indentation of operations and can cause a complete shut down of the final assembly line (Battini et al., 2013). To enable and foster JIS delivery so called "supermarkets" between the final assembly and the main warehouse are installed (Monden, 2011). These logistics supermarkets establish a new field of research, where several publications have already been made. One specific stream of research covers the allocation of supermarkets. Due to the high number of parts and potential allocation spots as well as the combinatorial size and overall complexity of the related planning task a quantitative decision making approach is required.

This paper contributes to theory and practice of the highly practice-relevant planning



problem of allocating logistics supermarkets within multi-production line facilities. Furthermore we provide a novel optimization model to solve it. To the knowledge of the authors this specific problem of allocating supermarkets within a multi-production line facility including all relevant restrictions has not been observed yet. We show the efficiency of the mathematical planning approach by comparing it to a manually generated solution applied in a real-world production setting of an German OEM. The model provided generates cost savings of nineteen percent.

The remainder of this paper is organized as follows. Section 2 gives an introduction of in-house logistics and line feeding concepts in the context of automotive production. Section 3 provides an overview of the related literature and reveals the contribution. In Section 4 the mathematical model is developed in form of a Mixed Integer Problem (MIP) and followed by an empirical case study and corresponding results in Section 5. Section 6 concludes the paper and shows further fields of research.

## **2. Line feeding concepts in automotive production**

This section gives a short introduction to in-house logistics in automotive production and aims to display the development of part feeding systems during the last decades. We highlight comparative advantages of changes and circumstances that lead to the introduction of supermarkets. Line feeding concepts in the automotive industry are characterized and the supermarkets approach is displayed in detail. To give an exhaustive overview of this part feeding system a critical review of the application of supermarkets is given. The description of the real-world planning problem concludes this section.

### *2.1. In-house logistics in automotive production*

In-house logistics concepts contain the storage of parts, transport of parts to the line and line-side presentation (Battini et al., 2013). The configuration of these approaches is closely linked to the characteristics of the corresponding assembly strategy. Automotive production facilities usually consists of body shop, paint shop, final assembly line and sub-assemblies (Lehmann and Kuhn, 2019). For the supply of these linear aligned manufacturing steps original equipment manufacturers (OEMs) develop and implement different logistics strategies. Boysen et al. (2015) give a comprehensive literature overview on part logistics in the automotive industry. In the premium market mixed-model assembly lines combined with

an assemble-to-order strategy are established in stabilized production environments (Müller and Kuhn, 2020). JIS concepts are applied at final assembly lines in assemble-to-order environments because at that point the diversity of variants is mainly created and the order penetration point is positioned (Olhager, 2003). This enables OEMs to produce a large number of car models, engine types and customized options cost efficiently (Boysen et al., 2008). Recent developments in technology, factory digitalization and alternative engines like electric vehicles and hydrogen technology pose new challenges for OEMs (Yin et al., 2018). Both, the number of variants and the heterogeneity of the products increases, this causes high efforts on the flow of material. As an alternative or enhancement to the mixed-model assembly line OEMs develop flexible production layouts (Kern et al., 2015; Hottenrott and Grunow, 2019). These systems require an adaptation of the production logistics and line feeding concepts (Sali and Sahin, 2016; Kern et al., 2017).

## *2.2. Assembly line feeding*

The transportation of parts from storage areas to work stations is called line feeding (Sali and Sahin, 2016) or part feeding (Choi and Lee, 2002; Emde and Boysen, 2012a). A classification scheme and related literature overview is presented by Schmid and Limère (2019) as well as Kilic and Durmusoglu (2015). The performed tasks include storage, handling, picking and transportation of parts. One major decision problem is the selection of the feeding policy, which means choosing between the alternatives line stocking, kitting and sequencing. Several authors such as Faccio et al. (2018), Sali et al. (2015), Sali and Sahin (2016), Faccio (2014), Limère et al. (2012) and Battini et al. (2010) provide solution approaches to determine the best policy decision. These line feeding policies are applied in accordance with the production of vehicles. In production environments with few heterogeneous products the assembly stations at the final assembly line are supplied from a single, centralized storage. Commonly the materials are delivered in big lot sizes (pallet wise) and stored directly at the final assembly line (Emde and Boysen, 2012a; Boysen and Emde, 2014). This approach is called line side stocking and requires more space at the final assembly line per part. But it causes less logistics effort in terms of traffic towards the final assembly line since enough material is stocked and between one or two re-fillments per day are sufficient (Emde and Boysen, 2012a). Since parts are stored in transportation packaging the picking effort of the workers at the final assembly line is higher. With the increase of part variants the pallets stored alongside the assembly

line raise in numbers. In combination with the increasing production volume more of each material has to be stored leading to a situation where the already limited space becomes even more scarce. Since the available space is too small to store a sufficient amount of each part

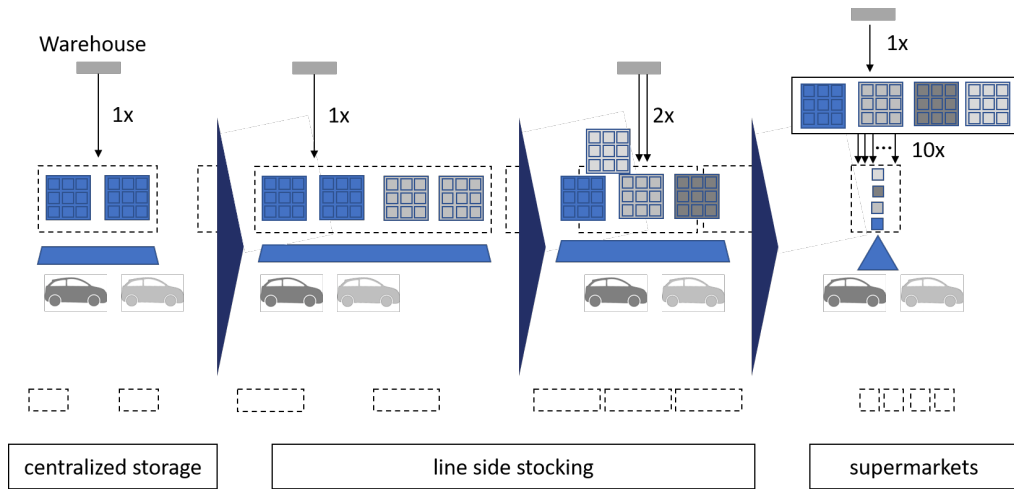


Figure 1: The development towards supermarkets

simultaneously the transportation rate towards the final assembly line has to be increased. In combination with the long distance towards the central storage a high transportation effort occurs and is accompanied by the risk of out of stock situations (Boysen et al., 2015). Additionally, since it takes very long to replace material at the final assembly line the system is very sensitive if there are any type of changes in the production sequence and the material supply has to be adopted accordingly (Boysen et al., 2015). So up to a certain level the rise in volume, models and equipment options could be handled by scaling the traditional feeding system. But at a certain point this system can not be used anymore, due to the scarce space and inefficient handling at the final assembly line.

Figure 1 displays the development of part feeding concepts and material handling. At first material is stored homogeneously at the final assembly line and refilled from time to time. The increasing variants aggravate the stockpiling and generates higher occupation of space. Additionally, the range of equipment options inside the cars increases and causes additional installation steps, an increase of material flow as well as storage areas. This leads to line side stocking approaches. Warehouses are relocated to low value per unit areas, where maintaining high inventories of a range of parts is viable. Accordingly, only the amount to cover a range of 1-2 hours of production is provided in the supermarket area. One important aspect of the supermarket concept is that the distance between its location and the final assembly line

becomes smaller than the original distance between retrieving center and the final assembly line.

Since not all parts of the car have undergone the development of increasing variants line side stocking is still a valid option for some parts (Faccio, 2014; Kilic and Durmusoglu, 2015). This usually concerns cheap, high volume parts with few to none variants. Such parts can be stored directly at the final assembly line without compromising on the costs. So there exists a heterogeneous landscape of line feeding concept visualized in Figure 2. Even though they are commonly used, they share their existence with other supply methods, which differentiate mainly by their so called "sequencing point" (Boysen et al., 2015). The sequencing point determines when the stream of material becomes identical to the sequence of produced cars. There are three commonly used sequencing points, which are also marked in Figure 2. The material is changed into the same sequence as required by the manufactured cars from homogeneous lot sizes or transportation lots either right away at the supplier (SP1), at the supermarket (SP2) or at the final assembly line (SP3).

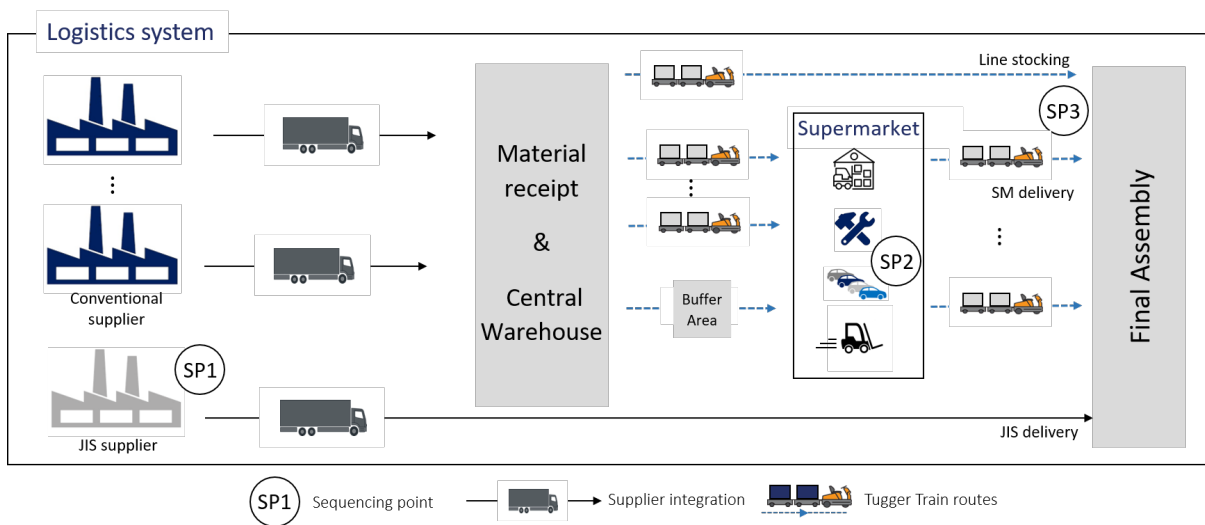


Figure 2: Hybrid logistics systems in automotive production facilities (based on Wörner (2014))

### 2.3. Logistics supermarkets

Supermarkets in the context of the automotive industry are decentralized logistics areas close to the final assembly line (Emde and Boysen, 2012a). They are usually replenished by central warehouses (Battini et al., 2013). Depending on the plant configuration supermarket concepts differ slightly but share common fundamental purpose. "Supermarket" is a suitable term to describe the logistics concept at hand, since it is similar to the concept of grocery

shopping from a customer point of view. In this case warehouse operators pick all the parts required to ensure the operation of the final assembly for a certain period of time (Battini et al., 2010). This analogy specifies all the relevant characteristics which are quite close to a traditional supermarket: You pick what you need, when you need it and in the right amount (Ohno, 2013). Transferred to the automotive production this means exactly the parts which are required at the final assembly line are picked and transported shortly before their installation. The quantity of parts is oriented on the consumption rate of the final assembly line in order to avoid overstocking as well as the related space and cost issues. As stated by Emde and Boysen (2012a) the concept of supermarkets is similar to the principle of cross-docks. Cross-docks are mostly established in retail logistics and describes the operation in which freight is unloaded from inbound vehicles and directly loaded into outbound vehicles (Van Belle et al., 2012). However, supermarkets feature more operations than the classic cross-docking concept, which basically handles and rearranges big lot sizes to smaller units. They are decentralized storage areas, which are integrated into the shop floor area and function as an intermediate storage for parts needed close by assembly lines (Emde and Boysen, 2012a). Figure 3 displays the integration of supermarkets in the production area. In most cases supermarkets are connected to the final assembly line via shuttles called tugging trains (short: tugging), tow trains (Battini et al., 2013) or locomotive (Boysen et al., 2015). They deliver parts according to a fixed schedule and on a fixed route from the supermarkets to the final assembly and collect empties. The un-powered trailers are connected to (often electrically) motorized towing machines (Boysen et al., 2015). The capacity of tow trains is sufficient to serve several stations during one tour, depending on the size of the material delivered. These tuggers can be operated by human operators or drive autonomously (Battini et al., 2013). Sometimes forklifts or statically installed conveyor systems are used instead (Boysen et al., 2015). The later ones tend to require a higher investment and offer less flexibility (Battini et al., 2013).

### 2.3.1. Supermarket functions

Supermarkets store parts over a short period of time and provide them according to the needs of the final assembly line (Emde and Boysen, 2012b). The main tasks can be classified into four groups as displayed in Figure 4. The supermarket fulfills *general operations* such as short term storage, unpacking and container management. Especially in the automotive

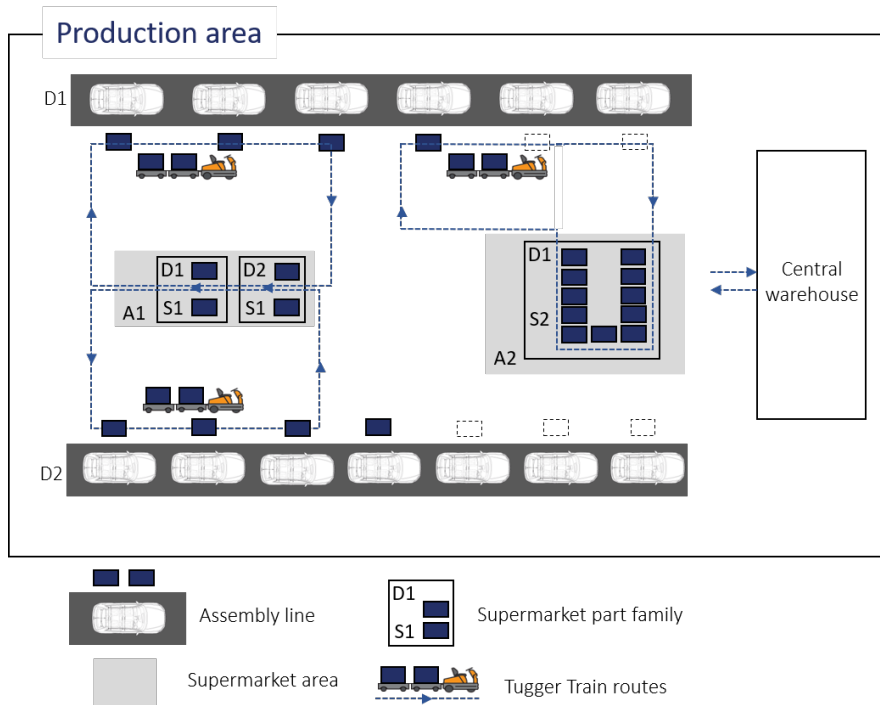


Figure 3: Integration of supermarkets in a network of mixed-model assembly lines

industry where a lot of specialized containers are used for transportation this function is important. The main point of supermarkets are the *assembly related operations*. The kitting involves picking a certain list of parts and arranging them into specialized containers to ease the assembly process (Caputo et al., 2015). Afterwards, these kits are delivered to the final assembly line (Boysen and Emde, 2014). Often kitting supermarkets fulfill several sub-assembly functions meaning some parts are pre-assembled before they arrive at the final assembly line. The next group of tasks are *sequence related operations*. Inside the supermarket parts are brought from homogeneous containers into an order of different parts according to their demand sequence at the final assembly line. The supermarket is also responsible for scheduling the arriving JIS parts, i.e., sending the tugger trains towards the final assembly line. Another important task is re-sequencing of the JIS material flow. If the initially planned sequence of the final assembly line changes unexpectedly, the material flow has to be re-arranged accordingly. The last segment are the *transport related operations*. They include loading, unloading and scheduling of tow trains. The loading process contains the efficient arrangement of containers and determination of the required number of wagons. The unloading process consists of the reception of the returned, empty container from the final assembly line.

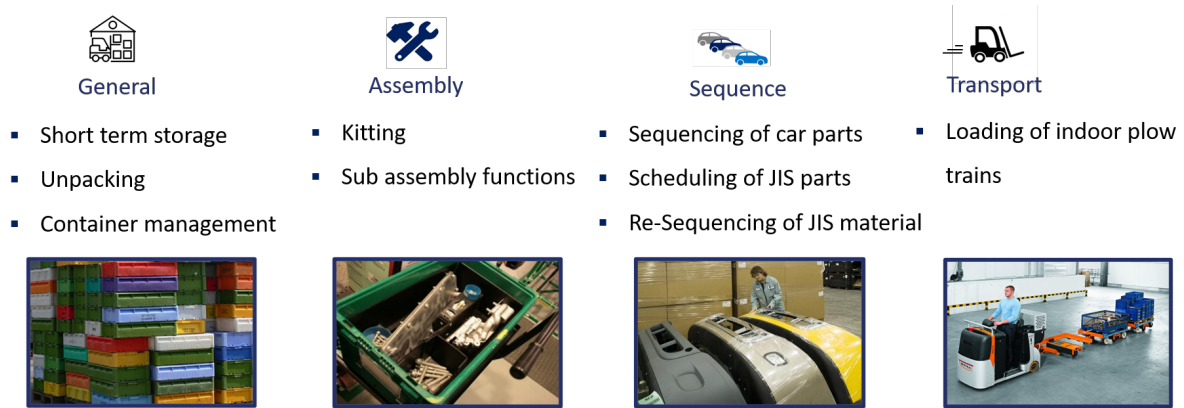


Figure 4: The four task groups of supermarkets

### 2.3.2. Content of supermarkets

A part usually comes in several variants, i.e., there are similar parts fulfilling the same function but have slightly different attributes (Boysen et al., 2015). For example steering wheels are all used to maneuver the vehicle but can come in different shapes, materials or with different optional functions, e.g., heating installations, radio control and speed assistant. The number of all possible variants is called a part family. Some part families are exclusively for one car model while others can be used for a range of models. They differ in their heterogeneity, e.g., there are part families with more or less variants.

A part family is usually stored unified especially if they are sequenced (Boysen et al., 2015). It is beneficial to allocate them together since they usually require the same containers as well as handling operations and are installed at the same position. Each part family requires a certain amount of space depending on the number of family members, material size, demand, required storage and handling equipment. The number of part families allocated together and the equipment make up a supermarket.

### 2.3.3. Location and configuration of supermarkets

Even though supermarkets fulfill the same tasks as listed in Section 2.3.1 their characteristics differ depending on the production facility in which they are integrated. Often supermarkets are positioned closely to the final assembly in order to ensure short transportation routes. But this is not necessarily the case. In some facilities supermarkets are located further away, e.g., in multi-production line facilities they are placed in between two or more final assembly lines. This causes a more distant positioning compared to the placement in single final assembly line facilities. Often supermarkets are u-shaped in order to optimize the

picking process (Boysen et al., 2015). The so called line-integrated supermarkets are another specialized version which depends on irremovable machinery. This configuration has no tow trains, because very close by workers can reach directly into the supermarkets (Boysen and Emde, 2014).

#### *2.3.4. Critical review of the supermarket concept*

For materials with a high number of variants or temporary demand the supermarket concept offers several advantages. Compared to the classic line stocking approach the number of pallets close to the final assembly line is reduced. Pallets at working stations occupy scarce space close to the assembly, hamper workers and material handling gets inflexible in terms of unforeseen events (Emde and Boysen, 2012a). Furthermore, the integration of supermarkets reduces effort and risks by avoiding long distance deliveries from central storage (Emde and Boysen, 2012a). Supermarkets enable the delivery of small lot sizes to the final assembly line (Battini et al., 2013). This enhances the possibility to react to sudden changes in the production program. Additionally, picking at the final assembly line is easier in terms of ergonomic aspects, since the parts are now stored in draw supporting boxes instead of transportation oriented containers (Battini et al., 2013). Furthermore, the worker triangle is reduced especially for JIS transport. The worker triangle represents the required operating radius of a worker on the final assembly line. The smaller the triangle, the smaller is the path length the worker has to move in order to get his material for the installation. Hence, the smaller the triangle the more efficient is the assembly process. Additionally, a small worker triangle reduces the error rate in terms of picking the wrong parts. The supermarket concept has its downsides when it comes to materials with low to none variants. The doubled handling effort, due to the additional logistics area, the required logistics space and the high transportation frequencies between the supermarkets and the final assembly line are no valid option under these conditions (Boysen et al., 2015). Concerning the aspect of risk the supermarkets with consequent JIS orientation causes a tremendous dependency of the final assembly line on the feeding process. Slight problems in the logistics process can result in line stoppage and results in substantial costs (Emde and Boysen, 2012a).



### *2.3.5. Planning Problem*

The supermarket allocation problem is a strategic planning problem that arises with major changes in the product mix, e.g., model change or model face lift. For the new car model the required part families have to be allocated in logistics areas in order to supply the final assembly. Each part family has to be allocated to exactly one location. From a logical point of view it would be technically possible to split part families and assign them to different supermarkets. However, to use economies of scale and avoid multiple safety stocks it is favored to assign part family as one and therefore to a single location. Everyone of these locations is capable of including a certain amount of part families, depending on the size of the location. The space required by each part family depends on the characteristics of the part family. They are heterogeneous meaning the consumption depends on the number of family members, size of the parts, required storage material and necessary handling equipment. The overall space consumption assigned to one supermarket is not allowed to exceed the available capacity at the location. Concerning the space consumption there are two additional requirements from a planning perspective. In order to avoid unused logistical space every location needs to have a certain minimum utilization. On the other hand each location should not exceed a certain level of utilization. This is due to the fact that the part families change over time, e.g., new variants of parts are added. In order to be able to add these parts to the same supermarket without re-adjusting the whole system, a certain threshold for flexibility is taken into account.

Another planning requirement is the partial and full pre-determination. Partial pre-determination allows specific part families only to be allocated to certain locations. This is necessary due to legal reasons. For example, in the automotive industry sub-contractors are used for logistical operations. Depending on the supplier contracts some parts are not allowed to be handled by sub-contractors. Another reason is that parts need special equipment which is not available at all locations and cannot be transferred, e.g., automatized depalletizing robot. The complete pre-determination is an even more rigid version. It requires to allocate a part family to one specific location. These part families cannot be excluded from the decision problem because there exist inter dependencies due to the tigger connections which will be explained next.

Every part family possesses at least one destination where its parts are installed at the final assembly line. Some part families feature more than one destination. This is often the case

when the same car model is assembled at different lines. Besides the variable transportation costs, which are already included in the overall assignment costs, there are fixed costs that occur with the installation of a tugger connection to the final assembly. For every destination of every part family allocated to a specific location there must be a tugger connection. One tugger connection can handle several part families but is also capacity restricted. Since several part families can share one connection there are inter dependencies. Thus, if one part family is completely pre-determined and requires a tugger connection it might be beneficial to allocate another part family with the same destination at that location.

The overall objective of this decision problem is to minimize the allocation costs which consists of a trade-off between the variable allocation costs and the costs arising from establishing tugger connections. The problem at hand can be applied to most automotive production sites which use the concept of logistics supermarkets, but is especially interesting for high volume plants with several final assembly lines.

### **3. Planning problems of supermarkets and related literature**

Planning tasks assigned to the supermarket allocation are classified by the usual categorization "strategic", "tactical" or "operational" depending on the planning horizon (Battini et al., 2013). As stated by Boysen et al. (2015) most supermarket related planning tasks are long-term or in other words strategic decision problems. This includes the location planning, which consists of the positioning of logistics areas and the allocation of parts to these areas. Emde and Boysen (2012a) tackle the problem of allocating such logistics areas. Nourmohammadi et al. (2019) consider the integrated supermarket location and transport vehicles selection problem. On a tactical level the routing and scheduling of tugger trains are the most important decision problems. These two problems are often solved together as in Zhou and Zhu (2020), Emde et al. (2018), Emde and Boysen (2012b) and Golz et al. (2012). In case of fixed tours only the scheduling problem is considered as in Emde and Gendreau (2017). The scheduling and loading of tow trains with milk-run delivery are investigated by Zhou and Zhu (2020) and with the focus on electric vehicles by Emde et al. (2018). Another scheduling problem concerning the work forces of so called line integrated supermarkets is addressed by Boysen and Emde (2014). On the operational level the efficient packing of the wagons from the tow trains is planned which is covered by Battini et al. (2013). Emde et al. (2012) tackle

the problem of optimally loading tow trains for JIS supply of mixed-model assembly lines. Battini et al. (2010) develop a step by step procedure which determines under which circumstances it is beneficial to manage parts via supermarkets. Schmid et al. (2020) introduces a model to assign parts to line feeding policies and to storage locations at the assembly stations in mixed-model assembly lines. As stated by Emde and Boysen (2012b) there still exists a gap in research concerning the allocation of supermarkets. The topics of the presented literature stream are related to our problem setting, but a planning approach for supermarket allocation with respect to handling and transportation costs of part families in a multi assembly line production facility has not been tackled so far.

In this paper we examine a supermarket allocation problem based on a real-world automotive production facility. The plant consists of several mixed-model assembly lines, which need to be fed with parts. These parts consists of part families, which have to be allocated to logistics areas. Every part family has at least one destination, which needs to be connected to the logistics area via a tugger train. The problem at hand is an important strategic planning task (Emde and Boysen, 2012a). It considers the positioning of a supermarket, but also the composition of the allocated supermarket. This means the combination of part families which make up the supermarket and the positioning are solved simultaneously. From a broader point of view the problem at hand is also related to the topic of facility layout problems and the Generalized Assignment Problem (GAP). The first topic engages with finding the most efficient arrangement of elements on the factory floor subject to different constraints in order to optimizing material handling costs (Pillai et al., 2011). Literature reviews on facility layout design problems are provided by Drira et al. (2007) and with the focus on multi-floor structure by Ahmadi et al. (2017). These types of problems consider facility shapes, layout configuration multi-floor layouts, material handling systems and devices. However, layout design problems are too complex for the present question of feeding mixed-model assembly lines with parts via supermarkets. The second topic is also closely related since the presented problem can be formulated with an extension of the GAP as introduced by Kuhn (1955). Therefore, the presented model belongs to the family of assignment problems. An extensive overview of the GAP is given by Cattrysse and Van Wassenhove (1992), Pentico (2007) and Öncan (2007). However, to solve the specific problem at hand the family of facility layout problems is too specific and detailed whilst the family of GAPs is not specific enough to meet

all the requirements of the supermarket allocation in multi line automotive facilities. The current paper, however, develops a novel and sophisticated solution approach capable of solving the optimization model developed for practically relevant problem sizes. We additionally conduct numerical experiments that are based on data gained from a real-life case study.

#### 4. Mathematical Modeling

In this section the mathematical model in form of a MIP is developed. First, all fundamental components such as sets and parameters of the modeling approach are defined. Afterwards the components of the cost function are described. In the third part a detailed description of the complete model is given.

##### 4.1. Sets and parameters

The supermarket allocation problem determines the optimal assignment of all part families  $p \in P$  to the available locations  $l \in L$ . An accumulation of part families at a location  $l$  is defined as a supermarket. Destinations  $d \in D$  mark the place at the final assembly line where part families are installed. Hence, there must be a transport between each location and the relevant final assembly line. Table 1 defines all applied sets and subsets.

**Table 1:** General sets and subsets

Sets	Description	Definition
$P$	Part families	$\{1, 2, \dots, p, \dots,  P \}$
$L$	Locations	$\{1, 2, \dots, l, \dots,  L \}$
$D$	Destinations	$\{1, 2, \dots, d, \dots,  D \}$
Subsets		
$P^{int}$	Internal part families	$P^{int} \subseteq P$
$P^{det}$	Pre-determined part families	$P^{det} \subseteq P$
$L^{ext}$	External locations	$L^{ext} \subseteq L$

##### 4.2. Cost function

To determine the overall costs for the assignment of part family  $p$  to a location  $l$  various aspects need to be taken into consideration. As displayed in Equation (1), the overall assignment costs  $c_{p,l}^{all}$  predicate on the components receiving costs  $c_{p,l}^{rec}$ , the picking costs  $c_{p,l}^{pick}$  and the

transportation costs  $c_{p,l}^{trans}$ . All three terms consist of several cost factors and are explained in depth in the following. Parameters and additional notations are displayed in Table 2.

*Receiving costs.* Receiving costs for part families consist of operational handling costs such as quality checks, inventory booking and the physical distribution of parts into shelves. Total receiving costs  $c_{p,l}^{rec}$ , displayed in Equation (2), consist of the sum of receiving costs caused in the warehouse entrance process  $c_l^{rec_{we}}$  and receiving costs at the supermarket location  $c_l^{rec_{pf}}$ . All types of receiving costs depend on the location  $l$  where they are handled. The sum of these two terms has to be multiplied by the share of the carrier  $sh_p^{carrier}$  which is consumed. Part feeding costs are all standardized to a single carrier unit. The share is determined by the size of the product and therefore depends on the part family  $p$ .

*Transportation costs.* Transportation costs presented in Equation (3) cover the economical effort that has to be taken into account to move parts from the supermarket area to the final assembly line. The overall transportation costs  $c_{p,l}^{trans}$  heavily depend on the distance  $t_{d,l}^{dis}$  to the final assembly line. The distance is multiplied with the variable transportation costs  $c^{tran_{var}}$  which describe the costs associated with the traveled distance, e.g., meters. These costs include energy consumption, vehicle attrition, and wage expenditures for the drivers. Additional to the variable transportation costs emerge fix costs  $c^{tran_{fix}}$  with every transport. These costs cover the loading of the truck and adding of trailers. The sum of fix and variable costs is multiplied by the frequency of transports  $t_p^{freq}$ . Depending on the size and demand of part family  $p$  the frequency differs among part families.

*Picking costs.* The picking costs  $c_{p,l}^{pick}$  are calculated per part family. These costs include operational handling inside the supermarket. They cover the distance of picking routes scanning process and sorting of parts.

### Allocation costs

$$c_{p,l}^{all} = c_{p,l}^{rec} + c_{p,l}^{pick} + c_{p,l}^{trans} \quad \forall p \in P, l \in L \quad (1)$$

### Receiving costs

$$c_{p,l}^{rec} = (c_l^{rec_{we}} + c_l^{rec_{pf}}) \cdot sh_p^{carrier} \quad \forall p \in P, l \in L \quad (2)$$

**Table 2:** Parameters for allocations costs

Parameters	Description	Definition
$c_{p,l}^{all}$	Allocation costs of part family $p \in P$ to location $l \in L$	$\in \mathbb{Q}^+$
$c^{tug}$	Costs per tugger train	$\in \mathbb{Q}^+$
$c_{p,l}^{rec}$	Receiving costs of part family $p \in P$ at location $l \in L$	$\in \mathbb{Q}^+$
$c_l^{rec_{we}}$	Entrance receiving costs at location $l \in L$	$\in \mathbb{Q}^+$
$c_l^{rec_{pf}}$	Part family receiving costs at location $l \in L$ $p \in P$	$\in \mathbb{Q}^+$
$sh_p^{carrier}$	Share of part family $p \in P$ on carrier system	$\in \mathbb{Q}^+$
$c_{p,l}^{pick}$	Picking costs of part family $p \in P$ at location $l \in L$	$\in \mathbb{Q}^+$
$c_{p,l}^{trans}$	Transportation costs for part family $p \in P$ at location $l \in L$	$\in \mathbb{Q}^+$
$t_{d,l}^{dis}$	Distance from location $l \in L$ to destination $d \in D$	$\in \mathbb{Q}^+$
$c^{tran_{var}}$	Variable transportation costs per meter	$\in \mathbb{Q}^+$
$c^{tran_{fix}}$	Fix transportation costs	$\in \mathbb{Q}^+$
$t_p^{freq}$	Transportation frequency of part family $p \in P$	$\in \mathbb{Q}^+$

### Transportation costs

$$c_{p,l}^{trans} = (t_{d,l}^{dis} \cdot c^{tran_{var}} + c^{tran_{fix}}) \cdot t_p^{freq} \quad \forall p \in P, l \in L, d \in D \quad (3)$$

The notation for the parameters of the model can be found in Table 3. Decision variable  $x_{p,l}$  determines which part family  $p$  is assigned to which location  $l$ . The second decision variable,  $y_{l,d}$ , defines the number of tugger trains which connect location  $l$  with destination  $d$ . The capacity requirements  $req_p$  of each part family  $p$  determines the consumption of space at the designated location. The total available space at each location is defined by  $cap_l$ . The minimum and maximum utilization of each location is determined by  $ut_{min}$  and  $ut_{max}$ , respectively. A certain subset  $P^{det}$  of all part families  $P$  is pre-determined. The precise mapping of locations and part families is defined by  $pre_{p,l}$ . Another important information is which part family needs to be transported to which destination at the final assembly line. This is given by  $m_{p,d}$ . A tugger train is required for the transport and every transport consumes a certain amount of capacity from the tugger. The overall capacity of each tugger is defined by  $t^{cap}$ .

**Table 3:** Parameters for the model

Parameters	Description	Definition
$TC_{SAP}$	Total costs	$\in \mathbb{Q}^+$
$x_{p,l}$	Allocation of part family $p$ to location $l$	$\in \{1, 0\}$
$y_{l,d}$	Number of tuggers from location $l \in L$ to destination $d \in D$	$\in \mathbb{N}^+$
$req_p$	Capacity requirements of part family $p \in P$	$\in \mathbb{N}^+$
$cap_l$	Capacity of location $l \in L$	$\in \mathbb{N}^+$
$pre_{p,l}$	Corresponding locations $l$ for pre-determined part families $p \in P^{det}$	$\in \{1, 0\}$
$m_{p,d}$	Mapping of part families $p \in P$ to destination $d \in D$	$\in \{1, 0\}$
$t^{cap}$	Tugger train capacity	$\in \mathbb{N}^+$
$ut_{max}$	Maximum utilization	$[0, 1]$
$ut_{min}$	Minimum utilization	$[0, 1]$

### 4.3. Model

#### Model SAP

$$\text{minimize } TC_{SAP} = \sum_{p \in P} \sum_{l \in L} c_{p,l}^{all} \cdot x_{p,l} + \sum_{l \in L} \sum_{d \in D} c^{tug} \cdot y_{l,d} \quad (4)$$

subject to

$$\sum_{l \in L} x_{p,l} = 1 \quad \forall p \in P \quad (5)$$

$$\sum_{p \in P} x_{p,l} \cdot req_p \leq cap_l \quad \forall l \in L \quad (6)$$

$$\sum_{p \in P} x_{p,l} \cdot req_p \leq cap_l \cdot ut_{max} \quad \forall l \in L \quad (7)$$

$$\sum_{p \in P} x_{p,l} \cdot req_p \geq cap_l \cdot ut_{min} \quad \forall l \in L \quad (8)$$

$$x_{p,l} = 0 \quad \forall p \in P^{int}, l \in L^{ext} \quad (9)$$

$$x_{p,l} = pre_{p,l} \quad \forall p \in P^{det}, l \in L \quad (10)$$

$$\sum_{p \in P} m_{p,d} \cdot x_{p,l} \leq y_{l,d} \cdot t^{cap} \quad \forall l \in L, d \in D \quad (11)$$

$$x_{p,l} \in \{0, 1\} \quad \forall p \in P, l \in L \quad (12)$$

$$y_{l,d} \in \mathbb{Z}^+ \quad \forall l \in L, d \in D \quad (13)$$

#### 4.3.1. Objective function

The objective function (4) minimizes the overall allocation costs  $TC_{SAP}$  and consist of two parts. The left-hand side of the equation determines the assignment costs when part family  $p$  is assigned to location  $l$ . The assignment is determined by the binary decision variable  $x_{p,l}$  being one in the case that a part family  $p$  is allocated to location  $l$  and zero in the other case. The right-hand side of the equation contains the costs of connecting supermarkets with tugger trains to the final assembly. The number of tuggers required to install a sufficient connection is determined by a second decision variable  $y_{l,d}$ . The decision variable is multiplied with the cost parameter  $c^{tug}$ .

#### 4.3.2. Constraints

Equation (5) ensures that each part family  $p$  is exactly allocated to one location  $l$ . Equation (6) makes certain that for every location  $l$  the provided space  $cap_l$  is not exceeded by the requirements  $req_{p,l}$  of the allocated part families  $p$ . Equation (7) guarantees the maximum utilization rule and Equation (8) enforces the minimum utilization rule. Equation (9) assures partial pre-determination and (10) enforces complete determination of part families. Equation (11) takes care that the correct tugger connection is installed and that the tugger capacity is sufficient. Equation (12) determines the decision variable to be binary. Equation (13) defines the decision variable  $y_{l,d}$  as integer.

## 5. Case study

This section presents the numerical results achieved when applying the model using simulated data and data from a real-life case study. The applied data set, the computational study and the results are displayed in detail.

### 5.1. Data set

The developed mathematical model is motivated by a reorganization project of a German premium manufacturer. The data required to feed the model was gathered throughout this project. The purpose of this model is to find out if there is an alternative approach to the current manual planning process. The resulting data set comprises: installation location of parts, route cycles of tugger trains, space requirements, picking costs, partial and full pre-determination of part families. An overview of the meta data of the case study can be observed



in Table 4. The real-world data set comprises 330 part family and 17 locations. They feed several assembly destinations positioned around three production lines.

**Table 4:** Case study meta data

Parameters	Value
Number of part families	330
Number of Locations	17
Number of Destinations	33
Internal part families	13 %
Pre-determined	4 %
Overcapacity	25 %
Internal locations	67 %
Capacity internal locations	50 %

### 5.2. Computational study

In order to get a better understanding of the model behavior a numerical study was conducted. It shows the influence of different parameters and model settings on the run time and overall feasibility in terms of practical application. Therefore, a variety of different problem instances is required. Since the case study consists only of one data set, a data generator is required to produce data sets with different characteristics based on random numbers. In order to avoid infeasible sets some characteristics of the mathematical model need to be taken into account when creating the random number instance generator. Hence, the created sets are not completely random. For example if one part family is pre-determined and also required to be in an internal location the generator has to ensure that the randomly picked pre-determination is one of the internal locations. The adjusted parameters for the generator are the same as the meta data described in Table 4. The number of locations and part families applied fulfill the requirements of large real-world production settings.

### 5.3. Results

In order to show the efficiency of the model developed we apply it on the real-world data set. As benchmark we take the currently applied and manually generated solution and evaluate it based on the same overall cost function that is used in the model. Beforehand we verify that the manually generated solution is feasible in order to guarantee comparability.

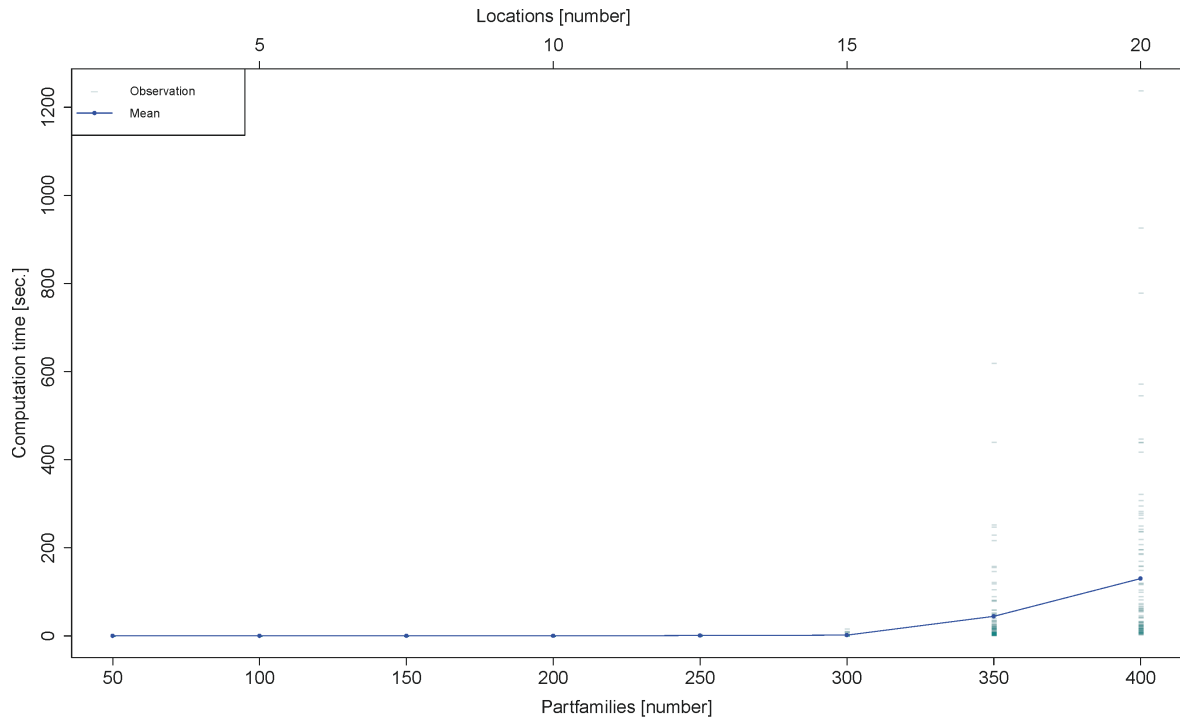


Figure 5: Analysis of the total computation time

The model is implemented within Gorubi Optimizer (version 9.0.0) The calculation is operated on an AMD Ryzen 9 3900X 12-Core Processor @ 3,97 GHz with 32 GB of RAM under Windows 10 Enterprise. The solution process terminates after a time limit of 24 hours.

The overall costs of the best found solution is 19 percent better compared to the manually generated solution. This is a favourable result since the material handling costs make up to 20–50 percent of the total operating costs of the facility layout (Chan et al., 2004). For the manually generated solution the ratio of allocation costs towards tugger costs is 3.5 to 1. The presented decision model creates a solution with a ration of 4 to 1. Taking a closer look at the results provides insides on the changing ratio. The presented model reduces the costs of both components, but major savings result from the reduction of the tugger costs. The overall reduction of 19 percent is composed by a 16 percent cost reduction of the allocation and a 30 percent cost reduction of the tuggers. Optimizing the tugger costs manually is a difficult task due to the high number of dependencies. Therefore, we assume that for creating the manual solution the tugger costs were neglected and a greedy algorithm concerning the allocation costs was applied. That is why the improvements of tugger costs is higher compared to the allocation costs.

The run time analysis in Figure 5 suggest that instance of the case study as described

in Table 4 should be solved optimally in a short amount of time. However, the calculations terminated after 24 without being able to proof optimality. We assume that this is due to the presence of many symmetrical solutions, which occur due to the same cost factors and capacity of some super markets.

The results show the potential of applied operations research methods in the automotive industries. Even a non-optimal solution from a standard solver brings a remarkable improvement compared to the current situation. With respect to the horizon of the planning problem (up to ten years) the computing time could also be extended to further improve the solution.

## 6. Conclusions and Prospects

This paper focuses on the part feeding of multi-line automotive manufacturing plants via supermarkets which are implemented between the central warehouse and the final assembly. Supermarkets are integrated in the shop floor area, have limited storage space and cover a variety of parts. These parts usually come in several variants summarized in so-called part families. The stock of parts ensures the operation of the final assembly for a certain period of time. Thus, supermarkets require constant delivery in small volumes from the central warehouse. The delivery routes are usually operated by tugger trains. Line feeding via supermarkets considerably differ from the classical concepts, e.g., JIS delivery or line stocking with full pallets next to the assembly line. The supermarket concept offers several advantages, especially for parts with a high number of variants, i.e., large part families, or temporary demand. To avoid multiple safety stocks it is favored to assign part families as one to a single location. Moreover, in real-world planning settings additional requirements apply, e.g., a minimum or maximum utilization level of supermarkets and a pre-determination of part families to certain locations. As a result, the supermarket concept constitutes a considerable challenge in automotive in-house logistics. We develop a novel mathematical model approach of supermarket allocation including the corresponding transportation costs. The numerical analyses using data of a multi-line automotive production plant clarify the efficiency of our approach compared to the solution manually generated in real-world.

The suggested modeling approach could be adapted and extended in several directions, leading to new challenges for further research. A possible next step could be the development of a heuristic in order to find a better solution in the same time as the standard solver.

Moreover, the approach is not limited to the automotive industry and could be transferred to other application areas that show great similarities to our problem setting. For example, bus, train or customized engineering industry display equivalent conditions, e.g., a build-to-order strategy, several production lines, high product variety and JIS supply patterns. Furthermore, the retail business operates micro stores, e.g., petrol station shops, supplying these stores with goods leads to noticeable logistics challenges. These stores have a low total sales volumes and the respective sales areas are very limited leading to highly frequent deliveries of small sizes (Kuhn et al., 2020). This has great similarities to our problem setting which can be further investigated.

The research on automotive logistics and JIS supermarkets leave plenty of opportunities for further studies. Especially from the background of increasing automation giving birth to new, highly flexible production concepts, e.g., modular production, the suggested model could be adapted. Flexible production concepts require the development of more decentralised material supplying strategies. With some adjustments the modeling and solution approach suggested could be adapted towards the requirements of modular production.

## References

- Ahmadi, A., Pishvae, M.S., Jokar, M.R.A., 2017. A survey on multi-floor facility layout problems. *Computers & Industrial Engineering* 107, 158–170.
- Battini, D., Boysen, N., Emde, S., 2013. Just-in-time supermarkets for part supply in the automobile industry. *Journal of Management Control* 24, 209–217.
- Battini, D., Faccio, M., Persona, A., Sgarbossa, F., 2009. Design of the optimal feeding policy in an assembly system. *International Journal of Production Economics* 121, 233–254.
- Battini, D., Faccio, M., Persona, A., Sgarbossa, F., 2010. “supermarket warehouses”: stocking policies optimization in an assembly-to-order environment. *The International Journal of Advanced Manufacturing Technology* 50, 775–788.
- Boysen, N., Emde, S., 2014. Scheduling the part supply of mixed-model assembly lines in line-integrated supermarkets. *European Journal of Operational Research* 239, 820–829.
- Boysen, N., Emde, S., Hoeck, M., Kauderer, M., 2015. Part logistics in the automotive industry: Decision problems, literature review and research agenda. *European Journal of Operational Research* 242, 107–120.
- Boysen, N., Flidner, M., Scholl, A., 2008. Assembly line balancing: Which model to use when? *International Journal of Production Economics* 111, 509–528.
- Caputo, A.C., Pelagagge, P.M., Salini, P., 2015. Modeling errors in kitting processes for assembly lines feeding. *IFAC-PapersOnLine* 48, 338–344.
- Cattrysse, D.G., Van Wassenhove, L.N., 1992. A survey of algorithms for the generalized assignment problem. *European journal of operational research* 60, 260–272.
- Chan, W., Chan, C., Kwong, C., 2004. Development of the main algorithm for a cellular manufacturing machine layout. *International journal of production research* 42, 51–65.
- Choi, W., Lee, Y., 2002. A dynamic part-feeding system for an automotive assembly line. *Computers & Industrial Engineering* 43, 123–134.
- Delfmann, W., Ten Hompel, M., Kersten, W., Schmidt, T., Stölzle, W., 2018. Logistics as a science: Central research questions in the era of the fourth industrial revolution. *Logistics Research* 11, 1–13.
- Drira, A., Pierreval, H., Hajri-Gabouj, S., 2007. Facility layout problems: A survey. *Annual Reviews in Control* 31, 255–267.
- Emde, S., Abedinnia, H., Glock, C.H., 2018. Scheduling electric vehicles making milk-runs for just-in-time delivery. *IIE Transactions* 50, 1013–1025.
- Emde, S., Boysen, N., 2012a. Optimally locating in-house logistics areas to facilitate JIT-supply of mixed-model assembly lines. *International Journal of Production Economics* 135, 393–402.
- Emde, S., Boysen, N., 2012b. Optimally routing and scheduling tow trains for JIT-supply of mixed-model assembly lines. *European Journal of Operational Research* 217, 287–299.
- Emde, S., Flidner, M., Boysen, N., 2012. Optimally loading tow trains for just-in-time supply of mixed-model assembly lines. *IIE Transactions* 44, 121–135.
- Emde, S., Gendreau, M., 2017. Scheduling in-house transport vehicles to feed parts to automotive assembly lines. *European Journal of Operational Research* 260, 255–267.
- Faccio, M., 2014. The impact of production mix variations and models varieties on the parts-feeding policy selection in a JIT assembly system. *The International Journal of Advanced Manufacturing Technology* 72, 543–560.
- Faccio, M., Cohen, Y., Kilic, H.S., Durmusoglu, M.B., 2015. Advances in assembly line parts feeding policies: a literature review. *Assembly Automation* 35, 57–68.

- Faccio, M., Gamberi, M., Bortolini, M., Pilati, F., 2018. Macro and micro-logistic aspects in defining the parts-feeding policy in mixed-model assembly systems. *International Journal of Services and Operations Management* 31, 433–462.
- Golz, J., Gujjula, R., Günther, H.O., Rinderer, S., Ziegler, M., 2012. Part feeding at high-variant mixed-model assembly lines. *Flexible Services and Manufacturing Journal* 24, 119–141.
- Hottenrott, A., Grunow, M., 2019. Flexible layouts for the mixed-model assembly of heterogeneous vehicles. *OR Spectrum* 41, 943–979.
- Inman, R.R., 2003. ASRS sizing for recreating automotive assembly sequences. *International Journal of Production Research* 41, 847–863.
- Kern, W., Lämmermann, H., Bauernhansl, T., 2017. An integrated logistics concept for a modular assembly system. *Procedia Manufacturing* 11, 957–964.
- Kern, W., Rusitschka, F., Kopytynski, W., Keckl, S., Bauernhansl, T., 2015. Alternatives to assembly line production in the automotive industry, in: *Proceedings of the 23rd International Conference on Production Research (IFPR)*.
- Kilic, H.S., Durmusoglu, M.B., 2015. Advances in assembly line parts feeding policies: a literature review. *Assembly Automation* 35, 57–68.
- Krcal, H.C., 2008. Strategische Implikationen einer geringen Fertigungstiefe für die Automobilindustrie. *Schmalenbachs Zeitschrift für betriebswirtschaftliche Forschung* 60, 778–808.
- Kuhn, H., Schubert, D., Holzapfel, A., 2020. Integrated order batching and vehicle routing operations in grocery retail—a general adaptive large neighborhood search algorithm. *European Journal of Operational Research* .
- Kuhn, H.W., 1955. The hungarian method for the assignment problem. *Naval research logistics quarterly* 2, 83–97.
- Lehmann, M., Kuhn, H., 2019. Modeling and analyzing sequence stability in flexible automotive production systems. *Flexible Services and Manufacturing Journal* 192, 349 – 368.
- Limère, V., Landeghem, H.V., Goetschalckx, M., Aghezzaf, E.H., McGinnis, L.F., 2012. Optimising part feeding in the automotive assembly industry: deciding between kitting and line stocking. *International Journal of Production Research* 50, 4046–4060.
- Monden, Y., 2011. *Toyota production system: an integrated approach to just-in-time*. CRC Press.
- Müller, M., Kuhn, H., 2020. Analyzing a centralized buffer in automotive production plants - a simulation study, in: Xu, X., Dessouky, M.I., Zhong, R.Y. (Eds.), *49th International Conference on Computers and Industrial Engineering 2019 (CIE49)*, Computers and Industrial Engineering. Curran Associates. pp. 455–463.
- Nourmohammadi, A., Eskandari, H., Fathi, M., Ng, A.H., 2019. Integrated locating in-house logistics areas and transport vehicles selection problem in assembly lines. *International Journal of Production Research* , 1–19.
- Ohno, T., 2013. *Das Toyota-Produktionssystem*. Campus Verlag.
- Olhager, J., 2003. Strategic positioning of the order penetration point. *International journal of production economics* 85, 319–329.
- Öncan, T., 2007. A survey of the generalized assignment problem and its applications. *INFOR: Information Systems and Operational Research* 45, 123–141.
- Pentico, D.W., 2007. Assignment problems: A golden anniversary survey. *European Journal of Operational Research* 176, 774–793.
- Pillai, V.M., Hunagund, I.B., Krishnan, K.K., 2011. Design of robust layout for dynamic plant layout prob-

- lems. *Computers & Industrial Engineering* 61, 813–823.
- Sali, M., Sahin, E., 2016. Line feeding optimization for just in time assembly lines: An application to the automotive industry. *International Journal of Production Economics* 174, 54 – 67.
- Sali, M., Sahin, E., Patchong, A., 2015. An empirical assessment of the performances of three line feeding modes used in the automotive sector: line stocking vs. kitting vs. sequencing. *International Journal of Production Research* 53, 1439–1459.
- Schmid, N.A., Limère, V., 2019. A classification of tactical assembly line feeding problems. *International Journal of Production Research* 57, 7586–7609.
- Schmid, N.A., Limère, V., Raa, B., 2018. Modeling variable space in assembly line feeding. *IFAC-PapersOnLine* 51, 164–169.
- Schmid, N.A., Limère, V., Raa, B., 2020. Mixed model assembly line feeding with discrete location assignments and variable station space. *Omega* , 102286.
- Strandhagen, J.O., Vallandingham, L.R., Fracapane, G., Strandhagen, J.W., Stangeland, A.B.H., Sharma, N., 2017. Logistics 4.0 and emerging sustainable business models. *Advances in Manufacturing* 5, 359–369.
- Van Belle, J., Valckenaers, P., Cattrysse, D., 2012. Cross-docking: State of the art. *Omega* 40, 827–846.
- Wörner, D., 2014. Sequenzbildung in der Automobilmontage anhand von materialorientierten Niveaustrangungsstrategien: Analyse der Auswirkungen auf die innerbetriebliche Materialversorgung. volume 106. Cuvillier Verlag.
- Yin, Y., Stecke, K.E., Li, D., 2018. The evolution of production systems from industry 2.0 through industry 4.0. *International Journal of Production Research* 56, 848–861.
- Zhou, B., Zhu, Z., 2020. Optimally scheduling and loading tow trains of in-plant milk-run delivery for mixed-model assembly lines. *Assembly Automation* 40, 511–530.

# Management of buffer systems in automotive stabilized production networks - a qualitative analysis

Mareike Müller

---

## Abstract

Automotive manufacturers are operating in global and cross-linked production networks. From a production and logistics point of view they act as consignors and consignees of material, components and car bodies within these networks. The demand for customized cars, rapidly changing market environments, local market regulations and technology leaps force companies to orient their operational activities towards more flexible and resilient production strategies. One promising method to deal with the evolving complexity, uncertainty and volatility is to establish a stabilized production system. This concept requires several prerequisites, above all a high degree of stability in the production process. Buffers are allocated to perform multiple functions in order to provide stability. Opposing objectives of stakeholders, unfavorable infrastructural settings and the lack of an integral planning process can be an obstruction towards effective buffer allocation in production networks. If not applied in an integrated approach considering all functions buffer capacity can lead to an adverse effect on the overall performance. Misaligned buffers lower the efficiency, reduce the flexibility and increase the complexity of production systems. This article presents trade-off observations and challenges system designers are confronted with during the allocation of buffers in stabilized production networks. The most significant trade-off is between the two competing objectives of stability and throughput. Best practice on how to implement buffers and manage the arising trade-off are presented.

*Keywords:* automotive production network, management and organisational control, stabilized production, buffer allocation, design of effective production

---



## 1. Introduction

Customization allows consumers to specify the products to their desires and is a current differentiating strategy chosen by many car manufacturers to compete in the highly competitive market (Brabazon et al., 2010; Kasiri et al., 2017). Manufacturing customized products with personalized features is facilitated by new technologies and concepts of Industry 4.0 (Wang et al., 2017). Market regulations increase production variety offered by original equipment manufactures (OEMs) even more (Ito and Sallee, 2018). To cope with the expanded model mix as well as variants in equipment options OEMs outsource sub-assemblies to shift product variety to upstream suppliers. Thereby, they diminish vertical integration at the production site and benefit from lower production and handling costs (Swaminathan and Nitsch, 2007). Saving costs by sourcing components to low wage countries is a long-standing trend and increases the quantity and geographical dispersion of suppliers. As a result of these developments, cars already comprise between 4,000 and 9,000 different components and the count of suppliers exceeds 1,000 (Unger, 2018). As a consequence of these trends OEMs are operating in highly global and cross-linked production networks (Bozarth et al., 2009; Boysen et al., 2011; Ruppel, 2015; Modrak et al., 2018).

From the perspective of an OEM complex production networks are difficult to design and manage (Wagner and Silveira-Camargos, 2012; Ivanov and Dolgui, 2020). One common approach to deal with the complexity of supply chains is to establish lean production concepts such as a stabilized production system (SPS). Leanly operated production sites are more capable of simultaneously achieving high levels of productivity and quality (Krafcik, 1988; Shah and Ward, 2003). To fully exploit these advantages a constant and high stability level within the network is necessary. In this context stability means that the production requirement forecast equals the actual production requirement (Inman and Gonsalvez, 1997). Many OEMs are stuck in a transformation process or struggle to maintain a constant and high stability level (Womack et al., 2007; Meissner, 2010; Lehmann and Kuhn, 2019). Blocking and starving as well as stochastic processing times are drivers for instability (Battini et al., 2009). Intermediate buffers for car bodies and components are allocated to compensate these effects. Buffers fulfill several functions, such as decoupling flow lines or re-sequencing the order (Müller and Kuhn, 2020). Production steps require different sets of buffer functions. However, the range of functions applied determines the type of retrieval strategy required,

e.g., random access or first in first out, and therefore they define the type of buffer needed, e.g., automated storage and retrieval system (AS/RS) or mix bank. As these types require different investment and restrict the limited floorspace to different degrees the assignment of buffer functions is an essential task for the long- and mid-term planning process of production networks.

In this article the operative processes that are carried out in case of sequence instability are linked to the required buffer functions. Furthermore, planning steps to successfully implement and manage buffer systems in real-world manufacturing systems are put into a framework and described in detail. To provide potential for further research arising trade-offs are revealed. A supportive organisational environment and favorable production setting facilitate the allocation and management of buffers in stabilized production networks.

The paper is structured as follows. Section 2 gives an overview of stabilized automotive production networks and envisions concepts to allocate buffers within this setting. The planning steps to allocate and implement buffer systems are given in section 3. Trade-offs system designers are confronted with and a buffer setting favorable to SPSs are discussed in Section 4. A summary and prospects for future research in Section 5 conclude this paper.

## **2. Buffer allocation in stabilized production networks**

In order to provide customized cars OEM's establish built-to-order strategies on highly flexible mixed-model assembly lines (MMAL) (Boysen et al., 2008; Volling et al., 2013). Production starts when the customer order is received and at the beginning of the production the customer order is assigned to a car body (Meyr, 2004). These concepts are integrated into complex production networks.

### *2.1. Automotive production networks*

Automotive production consists of the physically connected body shop, paint shop and final assembly line as well as buffer systems. Common descriptions of the production process conclude a simple one line production flow (Choi and Lee, 2002; Pierreval et al., 2007; Fournier and Agard, 2007; Boysen et al., 2015). Compared to real-world production systems, this single-line car body flow is an oversimplified assumption. The schematic overview in Figure 1 illustrates a fully assigned production plant embedded into a network. It contains the car body flow (CBF) along with the component flow (CF). The CBF is sequentially organized,

but production segments comprise several assembly lines. The resulting number of possible connections correspond to the number of potential CBF routings. There are two main buffers located in the CBF; one between the body/ paint shop and the second one between the paint shop/ final assembly. CFs are bidirectional as plants are a producer of components for other plants (source) or consignees (sink). Suppliers of components are either incorporated sub-assembly lines, other production sites or subcontractors. The CF includes buffer systems which are located at sources and sinks of connecting lines. In some networks an additional buffer, e.g., a distribution center to prepare JIS material, is located in between sources and sinks.

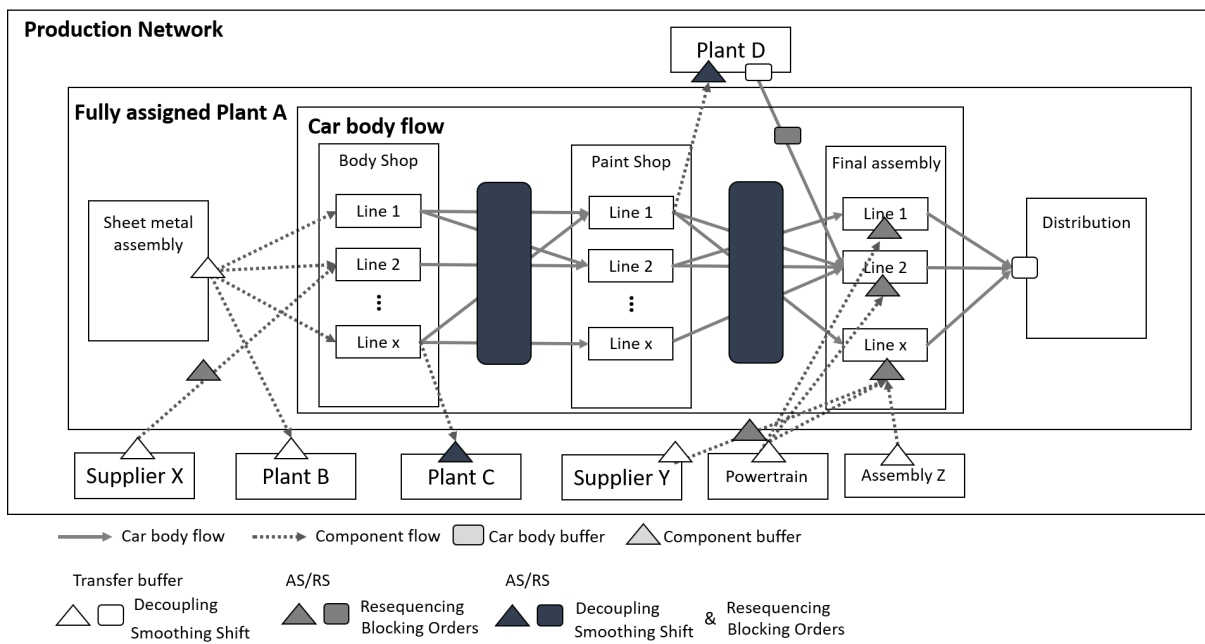


Figure 1: Schematic overview of buffer functions and locations in automotive production networks

Current developments in the automotive sector reinforce the expansion of the described networks. OEMs establish new cooperative ventures, e.g., with computer or telecommunications companies, to adapt non-automotive technologies (Attias, 2017). Manufacturers in the premium segment use purchasing cooperations, distribution networks and production platforms as an entry into less expensive segments (Göpfert et al., 2017). This step is necessary to meet the cost pressure as well as to manage the enormous variety of parts and components. Thus, operating production networks efficiently and ensuring a stable CBF as well as CF is the key success factor of OEMs nowadays (Gehr and Hellingrath, 2007).

## 2.2. Buffer functions in stabilized production systems

Key aspect of the SPS is planning and scheduling the sequence for the final assembly line several days before the start of the assembly process (Meissner, 2010). Figure 2 displays an SPS with JIS delivery patterns (Müller and Kuhn, 2020). A scheduled production and delivery date which serves as a requirement forecast is provided to costumers and suppliers. The fixed schedule and corresponding requirement forecast is the baseline for optimized material supplying approaches and reduces logistics handling expenses (Inman and Gonsalvez, 1997; Lehmann and Kuhn, 2019). A constant high stability level is the prerequisite for the applicability of the SPS concept. Stability means that a vehicle is manufactured exactly at its planned position in the sequence and at the fixed production time. Different key performance measures (KPIs) are applied to evaluate sequence stability (Müller et al., 2020). Sequence deviation, e.g., delayed or advanced orders, is penalized based on different calculation approaches.

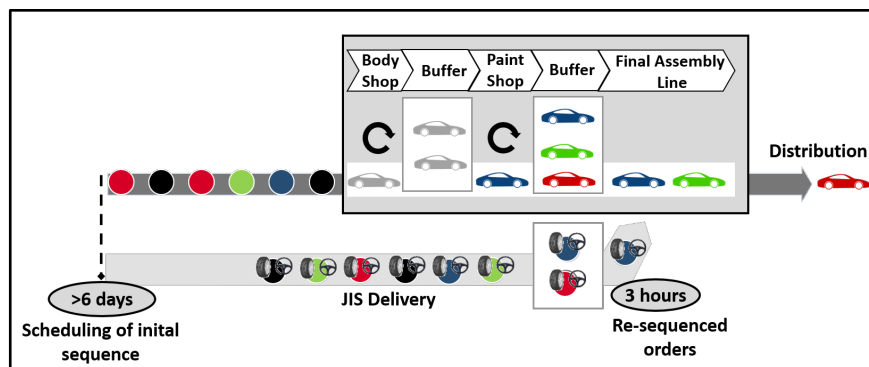


Figure 2: Automotive manufacturing in a stabilized production setting

The source for the requirement of buffers in production systems is variability, e.g., variability in process times, delivery times or demand rates (Hopp and Spearman, 2004). Buffers in SPS are required to maintain a constant high stability level and fulfill four functions. Foremost they serve as a decoupling module and avoid blocking and starving as it limits the throughput of the production (Shi and Men, 2003). Process blocking occurs when there is no more space to store work in process (WIP). When a production unit is idle and is forced to stop it is called starvation. Furthermore, buffers enable different takt times and shift models between production steps. The takt time of a production unit is the average time between the start of production of an order and the start of its successor. In production networks takt times vary, resulting in varying throughput per hour. To balance overall output different

shift models are applied (Wang et al., 2010). The stock in the buffer increases and decreases in regular cycles depending on the type of shift model. A number of car bodies is required to mitigate scrambling effects and re-sequence the sequence initially planned (Inman, 2010). Another function of buffers is to store blocked orders (Müller and Burges, 2020). If an order cannot be assembled at its original position it is blocked and the car body is stored in the buffer.

Buffer types engaged define possible arrival and retrieval strategies (Müller and Kuhn, 2020). Figure 1 gives an overview where buffer functions and types are commonly positioned in supply networks. To decouple production steps and to smooth differing production rates or varying shift models there is no special request towards the succession when retrieving orders. To carry out the re-sequencing and blocking function an AS/RS for the CBF and CF is mandatory. The linkage between the scrambling of an order and the requirement on car and component handling is exposed in Figure 3. It displays typical JIS supply patterns in SPS. The sequence of the CBF determines the order of material supply (Choi and Lee, 2002). If an order is blocked several operational tasks are executed (Boysen et al., 2015). From a logistical point of view material has to be re-sequenced; all components for blocked orders (number 6) are buffered and material for pulled ahead orders (number 7 and 8) are moved forward. The impact on the CBF is similar; blocked car bodies are stored in a buffer and succeeding orders are pulled ahead by one position.

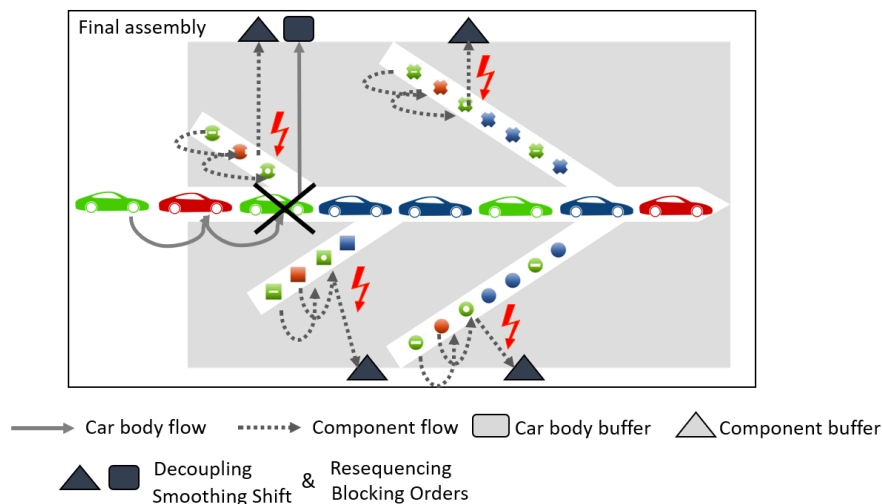


Figure 3: Impact of sequence scrambling on buffer requirements

### 2.3. Critical review on buffer systems in stabilized production networks

Buffers do not only give rise to advantages but imply some negative effects. They increase the WIP, raise the lead time, enhance investment and decelerate customer response (Glasserman and Yao, 1996; Kim and Lee, 2010). Additionally, they cover the limited floor space close to the assembly line (Lehmann and Kuhn, 2019). Buffers with random access require even more floorspace, a higher investment as well as operational expenses compared to mixed banks with parallel or loop lines (Inman, 2010). A steering logic is required to integrate them into the CBF as well as CF and to maintain a balanced stock (Van der Duyn Schouten and Vanneste, 1995). Too large or too small buffer capacity in stabilized production networks will lead to a number of disadvantages as displayed in Table 1. In the medium run both conditions lead to a decline of production efficiency.

Buffer capacity too high	Buffer capacity too low
Redundant functions and waste streams	Limited functions and restricted usability
Inefficacy of additional buffer capacity on the degree of stability	Instability and increased presence of scrambling
High amount of WIP, fluctuation of throughput and increased lead time, delays in delivery schedule	Loss of throughput because of blocking and starving, limited capability of smoothing shift models, limitation of operational intervention options
Additional costs on provision of resources, WIP, accumulation of operational processes, augmented complexity and opacity	Lost profit margin, additional costs on increased material handling effort and additional working shift

Table 1: Impact of misaligned buffer capacity

### 3. Planning and management of buffer systems in stabilized networks

A variety of planning problems arise when stabilized production networks are installed. An important long- and mid-term planning problem is the allocation of buffer systems and appendant functions. It comprises the stages of prearrangement, implementation and planning operational control processes. Figure 4 shows planning problems system designers are confronted with during the implementation. These are dealt with in the following.

*Business Case.* Stabilized systems require buffer types with random-access such as AS/RSs. A study on the impact of buffers helps to underline their potential benefits and recoverable amortization rate. In real-world manufacturing networks the impact on throughput is clearly measurable while sequence stability and its effects are difficult to quantify (Alden et al., 2006). The business case is based on considerations of production networks with no or little buffer capacity. Therefore, the production volume of the production steps are examined retroactively

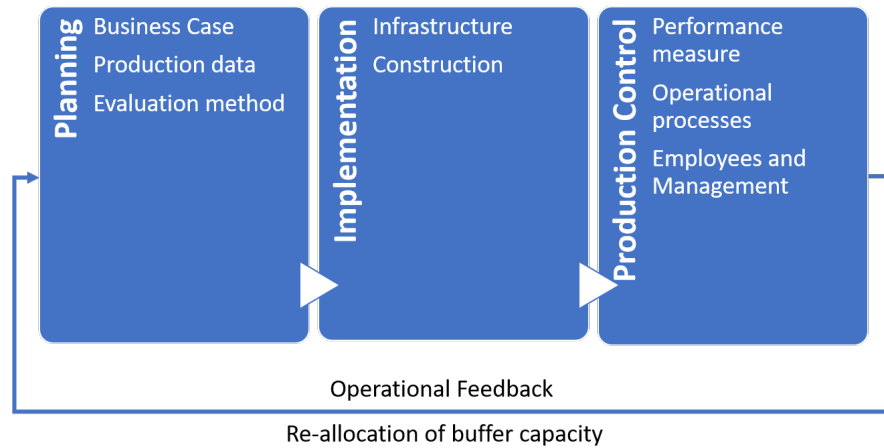


Figure 4: Planning and management of buffer systems in stabilized production networks

for a longer period of time, e.g., one year. Units that cause bottlenecks and reduce the planned throughput of production networks are of special interest. Loss in throughput is caused by unexpected downtime. In some cases additional working shifts are applied to compensate the minus. Loss in sales and resultant lack of profit margins as well as costs of additional shifts are priced by the controlling department. To calculate the amortization rate of an AS/RS the initial investment to install it is set into ratio with total costs of deficiency.

*Production Data.* The fundamental requirement to create a business case or to conduct studies is the availability of high quality data from the manufacturing system (Alden et al., 2006). The huge amount of data necessary to describe operational processes can be difficult to collect (Pierreval et al., 2007). All stakeholders of the process need to store relevant data consistently and with a sufficient level of quality. Another important issue is to harmonize production data collection by determining the frequency as well as the storage time (Kusiak, 2017). Especially in large production networks it is useful to establish a centralized database management to coordinate the manufacturing data throughout networks and ensure their integrity. The application of a data retrieval tool and a web-based management execution system (MES) to systematically track and document the transformation of the car body to a finished car is essential (Bourne et al., 2018). Responsibility of data management and data ownership has to be clearly defined. Data sovereignty should be assigned to operative production control centers in order to guarantee quality, completeness and accuracy. Furthermore, the operative production control centers should engage data analysts. They interpret, visualize and prepare production data as basis for decision-making.

*Evaluation Method.* The buffer allocation problem translates into an optimization problem opening a wide field of research. For a classification scheme and literature review see Demir et al. (2014) and Weiss et al. (2018). Analytic approaches on allocation of buffer space in flow lines take stochastic behaviour into account. However, these models are subject to limitations and assumptions because otherwise they would become too complex to calculate. Discrete event based simulation (DES) is commonly used to analyse real-world manufacturing systems and to address the buffer allocation problem without making limiting assumptions (Mahadevan and Narendran, 1993). DES is particularly suitable for the evaluation of complex queuing networks with limited buffer capacities and stochastic production times as well as the analysis of effects of the variables and their interactions (Montevecchi et al., 2007; Alfieri and Matta, 2012; Siebers et al., 2017). It only takes into consideration events that are of importance to the further course of the simulation, e.g., a car body entering a production step or leaving it. This method is efficient in terms of performance and allows system engineers to simulate production processes over a large period of time within minutes. In addition to the expertise of a simulation specialist DES requires production process know-how and extensive data sets. Information on production layouts, operating procedures, model parameters and product details need to be recorded and prepared. This induces further challenges, e.g., finding a suitable level of detail which suits the data availability and scope of the project. Modeling the functionality of certain instances as black boxes and embodying their effects in the applied data is one solution to avoid an unnecessarily high level of detail. The effort spent on deliberately choosing and developing a simulation model pays off in the long run. It avoids trial and error solution-seeking and helps system designers to prepare business cases and to forecast the performance of production networks.

*Infrastructure.* Once buffer functions are determined and capacity computed, performance demands are calculated and the most suitable location is selected. The criteria for determining the construction site include available clear height, size, quality and weight of car bodies as well as type of storage and retrieval systems. AS/RSs consist of storage racks, inbound/outbound stations and the most expensive part: cranes (Roodbergen and Vis, 2009). When an AS/RS is physically implemented the limits of its operating capabilities are fixed. Thus, the required throughput must be defined in advance. The performance of a system is defined as the number of storage and retrieval requests performed per time period (Bozer and White,



1982). The physical design determines performance and investment. Choosing more aisles reduces rack length or height if the capacity is maintained, but this design requires additional cranes. Shortening or lowering aisles reduces traveling distances and retrieval times, i.e., increases throughput.

*Construction.* The construction of buffer systems is seldom a greenfield project, i.e., they are integrated into existing networks. Transforming established production networks which are currently operating under different premises into an SPS is challenging (Lehmann and Kuhn, 2019). The expansion of infrastructure in brownfield projects is often not possible during operating time, which means it is bound to vacation closedown or will cause additional downtime. The second option leads to high opportunity costs. The planning of the implementation of a construction project has to start well in advance in order to adjust construction requirements to the ongoing production.

*Performance Measurement.* In SPS KPIs evaluate various parameters such as throughput, buffer filling level and stability level (Buchkin, 1998). It is important that the applied KPIs are discussed and agreed on with all stakeholders of the production network as well as reported on a regular basis. Suitable KPIs which reflect the status of the stabilized production network must be developed and implemented. E.g., the KPI stability level displays the effort of operational processes when changing the sequence initially planned by quantifying the amount of materials handling and the required buffer capacity (Müller et al., 2020). The target value of the stability level depends on the infrastructure and buffer capacity of the production network. By conducting simulation experiments, calibrating parameters and analyzing results an appropriate stability level can be estimated.

*Operational processes.* Optimal buffer filling levels identified by means of simulation experiments need to be maintained throughout production networks. Exceeding or falling below the planned buffer filling level has far-reaching consequences as describes in Table 1. Since buffer functions mentioned are only feasible if the filling level is steady, sensible operational control procedures need to be applied. An important prerequisite is to identify and compensate throughput losses immediately. Production units execute counter-measures such as additional working shifts on short-term. Another essential task in highly cross-linked, international production networks with JIS delivery approaches is decoupling differing shift models.

At best, working hours of production units joint by source / sink connections coincide. Differing working hours and varying public holidays enlarge buffer capacities required and limit the applicability of JIS strategies.

*Employees and Organisation.* The buffer allocation and operational processes are adapted towards requirements of SPS which restricts manufacturing managers and stakeholders in their decision-making. Limitations might reduce the efficiency of individual production units. Often, management incentives have not been restated or are aligned to short-term goals, e.g., throughput, and do not reflect effects on the stability level. The refusal of management and employees impede to fully leverage potentials of SPS. Lack of cooperation and in the worst case, rejection on an operational level is often caused by a gap of knowledge and information. Improving the understanding of SPS and buffer functions is one factor of success. Coordinating and conducting training sessions as well as the application of multipliers to pass on knowledge and experience is important. In this context it is necessary to adapt the cooperate culture towards lean, transparent and holistic viewpoints. Promoting a zero-defect culture and dealing with errors openly is a crucial success factor.

*Monitoring and evaluation of buffer systems.* Stabilized networks are sensitive constructions which need continuous adaption to new production settings. Re-allocating buffer capacity is required whenever there are substantial changes in product specifications or production settings (Xu et al., 2011). E.g., a major change of product assets when introducing a battery electric vehicle (BEV).

#### **4. Strategic decisions in stabilized networks**

A multiplicity of trade-offs arise when analyzing production networks. The concept of a trade-off suggests a scope for decision-making with full comprehension of advantages and disadvantages of each setup. The trade-offs occurring in SPSs mainly result from the requirements of the system along with the physical limits of buffer capacity. Both restrict production units in their decision-making.

*Trade-offs.* In SPS the production sequence of CBFs and CFs are aligned with the sequence of the final assembly line. Consequently, all upstream production segments are limited in modifying the sequence according to their needs. E.g., body and paint shop are restricted in

building body shell batches or paint batches. The limitation reduces the productivity of production facilities and leads to decreased local efficiency. Furthermore operating flexibility by compensating local throughput losses via counter-measure on short notice is a prerequisite to maintain stability. The resulting trade-off between benefits of individual production sections and comprehensive interests of the network need to be managed. Another question emerges considering measures to compensate negative effects of downtime over an extended period of time. Production losses can be offset by the balancing effects of buffers or through flexible production operations, such as running an extra shift. Whereas the first solution requires a high investment to provide the infrastructure, the latter has an impact on the contract of employment and implies high short-term variable costs caused by higher salaries.

The goals of sequence stability and throughput can not be attained simultaneously in SPS with limited buffer capacity, hence several trade-offs arise. In the CBF there is a conflict of target-setting when it comes to the management of the buffer functions. It is reflected in the utilization of buffer capacity. Re-sequencing maintains the stability level and decoupling production steps as well as smoothing shift models ensures a constant throughput. A certain amount of buffer capacity is required for re-sequencing, if the number decreases the stability level is reduced. If the capacity for decoupling is reduced blocking and starving occurs which lowers the throughput of production networks. Consequently, if the buffer filling level falls below the planned level a trade-off between throughput and stability level arises. A similar trade-off occurs in the course of the production process when orders overtake defected orders which are redirected to repair loops or off-line repair stations. This causes scrambling and lowers sequence stability. There are steering approaches such as line stop strategies to avoid scrambling (Robinson et al., 1990). The assembly line stops until defected orders are repaired, provoking a decline in the throughput (Han and Park, 2002).

At the final assembly there are several trade-offs concerning re-sequencing strategies (Lahmar and Benjaafar, 2007; Lim and Xu, 2017). It might be beneficial to ignore certain sequencing rules in order to maintain the stability (Boysen et al., 2010). This causes an unbalanced workload at the assembly line and induces costs, e.g., for additional workers. In case of defect or missing material orders are blocked or dispatched into the final assembly. The first causes scrambling and the second causes rework after the assembly line generating additional costs.

*Organisational environment.* The implementation of stabilized networks discloses an organizational problem which is beyond the tools and methodology of buffer allocation. A superior body independent of local concerns of the production segments has to balance the arising trade-offs. The management needs to place the decision-making authority and competence into the hands of a superordinated control, e.g., the operative production control center (Daniels and Burns, 1997). It decides which KPIs are taken into account and whether stability or throughput should prevail in the current status of production. Furthermore, clear responsibilities in inventory management ensure efficient as well as sustainable management. The optimum buffer filling levels are determined centrally and the responsibility for maintaining them is decentralised.

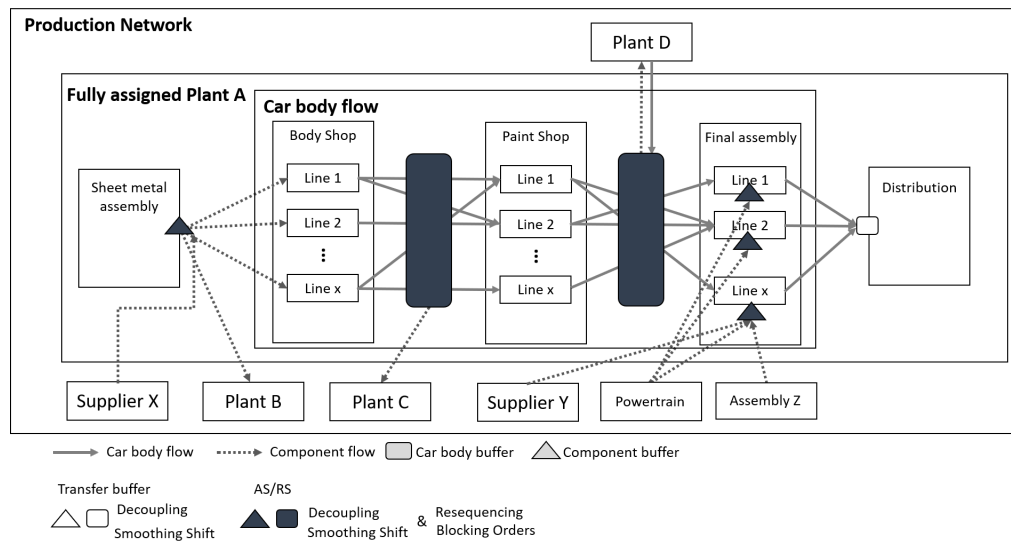


Figure 5: Favorable production setting in stabilized automotive production networks

*Production setting.* Most of the observed trade-offs in stabilized production networks are related to the allocation of the limited buffer capacity. To avoid excessive capacities and increase the flexibility of stabilized systems one shared buffer should be allocated at each connecting source-to-sink line. The functions of the buffers are transparently assigned and there is a clear structure. Figure 5 displays a favorable production setting. Compared to Figure 1 the number of buffer facilities in the network is significantly reduced. The required buffer capacity of connecting and intersecting lines are merged in one shared buffer. A shared buffer has a balancing effect on stock levels and flexibly exploits the available buffer capacity (Matta et al., 2006). It can significantly reduce the required buffer capacity in unreliable flow lines (Müller and Kuhn, 2020). Furthermore, shared buffers facilitate a clear responsibility

for the control of inventory and replenishment, which is an important factor to avoid the bullwhip effect (Lee et al., 1997).

## 5. Summary and further research

This paper tackles the question of how to allocate buffers in stabilized automotive production networks effectively and efficiently. JIS supply chain patterns are prevalent in these networks and induce the necessity of stabilized production environments. Buffers are required to ensure the stability as well as throughput and fulfill several functions. Therefore, an optimal buffer filling level determined by means of a simulation study must always be maintained. Both too high as well as too low capacity lead to disadvantages and decrease productivity. An optimal set up of buffers consists of shared buffers that cover all required functions and reduce the total amount of required buffer facilities. Allocating buffers in real-world manufacturing networks confront system designers with a broad spectrum of obstacles and trade-offs. Most of them are connected to the requirements of stabilized systems and the physical limits of buffer capacity. Production units are limited in their decision making to maintain the stability level of the network. There is a trade-off between keeping a high level of stability and maintaining the throughput. A centralised decision-making authority should balance the level of stability and throughput.

While this paper is intended to stimulate discussion and enlarge the research agenda of stabilized production networks, it offers several opportunities for future research. To quantify effects of sequence scrambling or instability is a research question of practical relevance. The planning problems and obstacles system designers are confronted with could be further investigated. Future studies should take the trade-off between sequence stability and throughput into consideration. Therefore the costs generated by additional material handling and throughput losses should be identified and optimized. A next step could be to conduct a large-scale empirical survey in order to expose efficient stability levels for different production settings.

Research on stabilized production systems certainly is important for the advancement of efficient manufacturing in the automotive industry. Extending this concept to more sustainable production would be a highly up-to-date topic. Additional research is needed to adapt the concept to other industries, e.g., the health care or retail food sector.

## References

- Alden, J.M., Burns, L.D., Costy, T., Hutton, R.D., Jackson, C.A., Kim, D.S., Kohls, K.A., Owen, J.H., Turnquist, M.A., Veen, D.J.V., 2006. General motors increases its production throughput. *Interfaces* 36, 6–25.
- Alfieri, A., Matta, A., 2012. Mathematical programming formulations for approximate simulation of multistage production systems. *European Journal of Operational Research* 219, 773–783.
- Attias, D., 2017. The automobile world in a state of change, in: Attias, D., Mira-Bonnardel, S. (Eds.), *The Automobile Revolution*. Springer, pp. 7–20.
- Battini, D., Persona, A., Regattieri, A., 2009. Buffer size design linked to reliability performance: A simulative study. *Computers & Industrial Engineering* 56, 1633–1641.
- Bourne, M., Melnyk, S., Bititci, U.S., 2018. Performance measurement and management: Theory and practice. *International Journal of Operations & Production Management* 38, 2010–2021.
- Boysen, N., Emde, S., Hoeck, M., Kauderer, M., 2015. Part logistics in the automotive industry: Decision problems, literature review and research agenda. *European Journal of Operational Research* 242, 107–120.
- Boysen, N., Fliedner, M., Scholl, A., 2008. Assembly line balancing: Which model to use when? *International Journal of Production Economics* 111, 509–528.
- Boysen, N., Fliedner, M., Scholl, A., 2010. Level scheduling under limited resequencing flexibility. *Flexible Services and Manufacturing Journal* 22, 236–257.
- Boysen, N., Golle, U., Rothlauf, F., 2011. The car resequencing problem with pull-off tables. *Business Research* 4, 276–292.
- Bozarth, C.C., Warsing, D.P., Flynn, B.B., Flynn, E.J., 2009. The impact of supply chain complexity on manufacturing plant performance. *Journal of Operations Management* 27, 78–93.
- Bozer, Y.A., White, J.A., 1982. Travel-time models for automated storage/retrieval systems. *IIE Transactions* 16, 329–338.
- Brabazon, P.G., MacCarthy, B., Woodcock, A., Hawkins, R.W., 2010. Mass customization in the automotive industry: comparing interdealer trading and reconfiguration flexibilities in order fulfillment. *Production and Operations Management* 19, 489–502.
- Buchkin, J., 1998. A comparative study of performance measures for throughput of a mixed model assembly line in a jit environment. *International Journal of Production Research* 36, 2669–2685.
- Choi, W., Lee, Y., 2002. A dynamic part-feeding system for an automotive assembly line. *Computers & Industrial Engineering* 43, 123–134.
- Daniels, R.C., Burns, N.D., 1997. A framework for proactive performance measurement system introduction. *International Journal of Operations & Production Management* 17, 100–116.
- Demir, L., Tunali, S., Eliyi, D.T., 2014. The state of the art on buffer allocation problem: A comprehensive survey. *Journal of Intelligent Manufacturing* 25, 371–392.
- Van der Duyn Schouten, F., Vanneste, S., 1995. Maintenance optimization of a production system with buffer capacity. *European journal of operational research* 82, 323–338.
- Fournier, X., Agard, B., 2007. Improvement of earliness and lateness by postponement on an automotive production line. *International Journal of Flexible Manufacturing Systems* 19, 107–121.
- Gehr, F., Hellingrath, B., 2007. Vorwort, in: Gehr, F., Hellingrath, B. (Eds.), *Logistik in der Automobilindustrie: Innovatives Supply Chain Management für wettbewerbsfähige Zulieferstrukturen*. Springer-Verlag Berlin Heidelberg. VDI-Buch, pp. VII – VIII.
- Glasserman, P., Yao, D.D., 1996. Structured buffer-allocation problems. *Discrete Event Dynamic Systems* 6,

9–41.

- Göpfert, I., Schulz, M., Wellbrock, W., 2017. Trends in der Automobillogistik, in: Göpfert, I., Braun, D., Schulz, M. (Eds.), *Automobillogistik: Stand und Zukunftstrends*. 3 ed.. Springer Gabler, Wiesbaden, pp. 1–21.
- Han, M.S., Park, D.J., 2002. Optimal buffer allocation of serial production lines with quality inspection machines. *Computers & Industrial Engineering* 42, 75–89.
- Hopp, W.J., Spearman, M.L., 2004. To pull or not to pull: what is the question? *Manufacturing & service operations management* 6, 133–148.
- Inman, R.R., 2010. Asrs sizing for recreating automotive assembly sequences. *International Journal of Production Research* 41, 847–863.
- Inman, R.R., Gonsalvez, D.J., 1997. The causes of schedule instability in an automotive supply chain. *Production and Inventory Management Journal* 38, 26.
- Ito, K., Sallee, J.M., 2018. The economics of attribute-based regulation: Theory and evidence from fuel economy standards. *The Review of Economics and Statistics* 100, 319–336.
- Ivanov, D., Dolgui, A., 2020. Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. a position paper motivated by covid-19 outbreak. *International Journal of Production Research* 58, 2904–2915.
- Kasiri, L.A., Cheng, K.T.G., Sambasivan, M., Sidin, S.M., 2017. Integration of standardization and customization: Impact on service quality, customer satisfaction, and loyalty. *Journal of Retailing and Consumer Services* 35, 91–97.
- Kim, S., Lee, H.J., 2010. Allocation of buffer capacity to minimize average work-in-process. *Production Planning & Control* 12, 706–716.
- Krafcik, J.F., 1988. Triumph of the lean manufacturing system. *Sloan Management Review* 30, 1–12.
- Kusiak, A., 2017. Smart manufacturing must embrace big data. *Nature* 544, 23–25.
- Lahmar, M., Benjaafar, S., 2007. Sequencing with limited flexibility. *IIE Transactions* 39, 937–955.
- Lee, H.L., Padmanabhan, V., Whang, S., 1997. Information distortion in a supply chain: The bullwhip effect. *Management science* 43, 546–558.
- Lehmann, M., Kuhn, H., 2019. Modeling and analyzing sequence stability in flexible automotive production systems. *Flexible Services and Manufacturing Journal* 192, 349.
- Lim, A., Xu, Z., 2017. Searching optimal resequencing and feature assignment on an automated assembly line. *Journal of the Operational Research Society* 60, 361–371.
- Mahadevan, B., Narendran, T.T., 1993. Buffer levels and choice of material handling device in flexible manufacturing systems. *European Journal of Operational Research* 69, 166–176.
- Matta, A., Runchina, M., Tolio, T., 2006. Automated flow lines with shared buffer, in: Liberopoulos, G., Papadopoulos, C.T., Tan, B., Smith, J.M., Gershwin, S.B. (Eds.), *Stochastic Modeling of Manufacturing Systems*. Springer-Verlag, s.l., pp. 99–120.
- Meissner, S., 2010. Controlling just-in-sequence flow-production. *Logistics Research* 2, 45–53.
- Meyr, H., 2004. Supply chain planning in the german automotive industry. *OR Spectrum* 26.
- Modrak, V., Helo, P.T., Matt, D.T., 2018. Complexity measures and models in supply chain networks. *Complexity* 2018, 1–3.
- Montevecchi, J.A.B., de Pinho, A.F., Leal, F., Marins, F.A.S., 2007. Application of design of experiments on the simulation of a process in automotive industry.
- Müller, M., Burges, U., 2020. Herausforderungen bei der Dimensionierung eines zentralen Entkopplungsmoduls in der Variantenfließfertigung und Darstellung eines selbstregulierenden Kreislaufsystems

- für Transportmittel., in: Mayer, G., Pöge, C., Spieckermann, S., Wenzel, S. (Eds.), *Ablaufsimulation in der Automobilindustrie*. Springer Vieweg. in Springer Fachmedien Wiesbaden GmbH, pp. 217–229.
- Müller, M., Kuhn, H., 2020. Analyzing a centralized buffer in automotive production plants - a simulation study, in: Xu, X., Dessouky, M.I., Zhong, R.Y. (Eds.), *49th International Conference on Computers and Industrial Engineering 2019 (CIE49)*, Computers and Industrial Engineering. pp. 455–463.
- Müller, M., Lehmann, M., Kuhn, H., 2020. Measuring sequence stability in automotive production lines. *International Journal of Production Research* 0, 1–21.
- Müller, M., Kuhn, H., 2020. Shared buffer allocation in stabilized automotive production. *Forthcoming*.
- Pierreval, H., Bruniaux, R., Caux, C., 2007. A continuous simulation approach for supply chains in the automotive industry. *Simulation Modelling Practice and Theory* 15, 185–198.
- Robinson, L.W., McClain, J.O., Thomas, L.J., 1990. The good, the bad and the ugly: Quality on an assembly line. *International Journal of Production Research* 28, 963–980.
- Roodbergen, K.J., Vis, I.F., 2009. A survey of literature on automated storage and retrieval systems. *European Journal of Operational Research* 194, 343–362.
- Ruppel, D., 2015. Hindernisse und Herausforderungen bei der Implementierung von Ganzheitlichen Produktionssystemen. *Arbeitspapier* 41, 1–45.
- Shah, R., Ward, P.T., 2003. Lean manufacturing: Context, practice bundles, and performance. *Journal of Operations Management* 21, 129–149.
- Shi, L., Men, S., 2003. Optimal buffer allocation in production lines. *IIE Transactions* 35, 1–10.
- Siebers, P.O., Macal, C.M., Garnett, J., Buxton, D., Pidd, M., 2017. Discrete-event simulation is dead, long live agent-based simulation! *Journal of Simulation* 4, 204–210.
- Swaminathan, J.M., Nitsch, T.R., 2007. Managing product variety in automobile assembly: The importance of the sequencing point. *Interfaces* 37, 324–333.
- Unger, T., 2018. Automotive industry & reach strategy & challenges for authorization. URL: [https://echa.europa.eu/documents/10162/13587/candidate\\_list\\_industry\\_unger\\_hyundai\\_en.pdf](https://echa.europa.eu/documents/10162/13587/candidate_list_industry_unger_hyundai_en.pdf).
- Volling, T., Matzke, A., Grunewald, M., Spengler, T.S., 2013. Planning of capacities and orders in build-to-order automobile production: A review. *European Journal of Operational Research* 224, 240–260.
- Wagner, S.M., Silveira-Camargos, V., 2012. Managing risks in just-in-sequence supply networks: Exploratory evidence from automakers. *IEEE Transactions on Engineering Management* 59, 52–64.
- Wang, J., Hu, Y., Li, J., 2010. Transient analysis to design buffer capacity in dairy filling and packing production lines. *Journal of Food Engineering* 98, 1–12.
- Wang, Y., Ma, H.S., Yang, J.H., Wang, K.S., 2017. Industry 4.0: a way from mass customization to mass personalization production. *Advances in Manufacturing* 5, 311–320.
- Weiss, S., Schwarz, J.A., Stolletz, R., 2018. The buffer allocation problem in production lines: Formulations, solution methods, and instances. *IIE Transactions* 51, 456–485.
- Womack, J.P., Jones, D.T., Roos, D., 2007. *The machine that changed the world: the story of lean production; Toyota's secret weapon in the global car wars that is revolutionizing world industry*. Business. 1. pb. ed., Free Press, New York, NY.
- Xu, T., Moon, D.H., Baek, S.G., 2011. A simulation study integrated with analytic hierarchy process (ahp) in an automotive manufacturing system. *Simulation* 88, 450–463.