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Coupling order release methods with autonomous control methods – an assessment of potentials by literature review and discrete event simulation

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Abstract: Production planning and control faces increasing uncertainty, dynamics and complexity. Autonomous control methods proved themselves as a promising approach for coping with these challenges. However, there is a lack of knowledge regarding the interaction between autonomous control and precedent functions of production planning and control. In particular, up to now previous research has paid no attention to the influence of order release methods on the efficiency of autonomous control methods. Thereby, many researchers over the last decades provided evidence that the order release function has great influence on the logistic objective achievement in conventional production systems. Therefore, this paper examines the influence of order release methods on the efficiency of autonomous control methods by both theoretic evaluation and discrete event simulation. The simulation results indicate an overall high influence. Moreover, the logistic performance differs considerably depending on the implemented order release methods and the combinations of order release methods with autonomous control methods. The findings highlight demand for further research in this field.

Key words: autonomous control, order release, production control, reactive scheduling.

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1. Introduction

Production planning and control (PPC) has to cope with increasing complexity, dynamics and uncertainty (Kim & Duffie, 2004; Westphal, 2001). Complexity is caused by the number and variety of elements and relations in a production system (Westphal, 2001). Dynamics is induced by the change of characteristics of elements and relations in time (Wyssusek, 1999). Uncertainty is defined as difference between required and available information, both about the current and the future system state and future events (Leisten, 1996). For the planning and control of production systems with a high degree of uncertainty, reactive scheduling approaches are generally proposed (Byeon, Wu & Storer, 1998; Gan & Wirth, 2005; Lawrence & Sewell, 1997; Sabuncuoglu & Karabuk, 1999). In this context, autonomous control methods proved themselves as a promising approach for coping with increasing dynamics and complexity in logistic processes (Scholz-Reiter & Freitag, 2007b). Thereby, they focus on the achievement of logistic objectives. However, also the preceding order release function has significant influence on the logistic objectives achievement in conventional, i.e. non-autonomous production systems (Qi, Sivakumar & Gershwin, 2009; Wein & Chevalier, 1992). Generally, order release methods impose the boundaries, within control methods operate. Up to now research has paid no attention to the influence of order release methods other than immediate order release on the efficiency of autonomous control methods.

Table 1. Review of previous research.

Order release method: release/ creation criteria ➢ **Research on autonomous control ⮟**	None/ Immediate release with deterministic plan dates	Periodic influx with immediate release (e.g. sinus)	WIP regulating approach without load balance	Approach with workstation specific load balance
Barenji, Barenji & Hashemipour (2014)		x		
Sudo & Matsuda (2013)	x			
Owliya, Saadat, Anane & Goharian (2012)	x			
Park & Tran (2012)	x			
Pach, Bekrar, Zbib, Sallez & Trentesaux (2012)	x			
Rekersbrink (2012)		x		
Wang, Tang, Gu, Zheng, Yuan & Tang (2012)	x			
Windt, Becker, Jeken & Gelessus (2010)		x		
Scholz-Reiter, Görges, Jagalski & Naujok (2010)	x			
Pannequin, Morel & Thomas (2009)	x			
Wang & Lin (2009)	x			
Duffie & Shi (2009); Duffie, Roy & Shi (2008)		x		
Leitão & Restivo (2008)	x			
Scholz-Reiter, Jagalski & Bendul (2008); de Beer (2008); Scholz-Reiter, Freitag, de Beer & Jagalski (2006)		x		
Xiang & Lee (2008)		x		
Tsutsui & Liu (2007)	x			
Reaidy, Massotte & Diep (2006)		x		
Wong, Leung, Mak & Fung (2006)	x			
Armbruster, de Beer, Freitag, Jagalski & Ringhofer (2006)	x	x		
Kornienko, Kornienko & Priese (2004)	x			
Siwamogsatham & Saygin (2004)		x		
Cicirello & Smith (2001)	x	x		

Table 1 gives an overview of previous research on autonomous control in a broader sense concerning the applied order release methods according to the classification depicted later in section 2.3. The overview reveals that classes of WIP regulating approaches and load balancing approaches have not yet been examined in combination with autonomous control approaches. Nevertheless, WIP regulating approaches and load balancing approaches are in focus of scientific consideration, as many recent publications to these topics reveal. Ostgathe (2012) for instance applies the Workload Control approach in combination with the least slack sequencing rule in his approach examining autonomous disruption management. It is generally suggested to apply simple sequencing rules in combination with these release approaches (Land, Stevenson & Thürer 2012). Due to the proven high impact of order release methods in non-autonomous systems, this paper investigates the effect of the application of order release methods in autonomously controlled production systems.

2. Fundamentals

2.1. Scheduling in the context of production planning and control

Production planning and control provides the basis for organising and executing the production process (Nyhuis & Wiendahl, 2008). The basic planning tasks are the production program planning, the production requirements planning, the in-house production planning with scheduling as a subtask, and the planning and control of external production (cf. Figure 1). The first task creates a production program, containing the primary demand for each product and planning period based on market and sales forecasts. This step is also known as production planning or master scheduling (Pinedo, 2008). The subsequent requirement planning derives the secondary demand from the production program, i.e. the required material and resources. Therefore, production orders are generated, roughly scheduled and the required production capacities are computed and adjusted. Based on the results of these planning steps, the make-or-buy decision determines which parts of the production are procured externally and which are produced in-house. External production for example might be relevant if the demand exceeds available in-house production capacities. In case of in-house production, production planning determines batch sizes, detailed scheduling of production orders and the availability check of required resources. Diligent data management is the basis for all these tasks. (Schuh, 2006; Wiendahl, 2005).

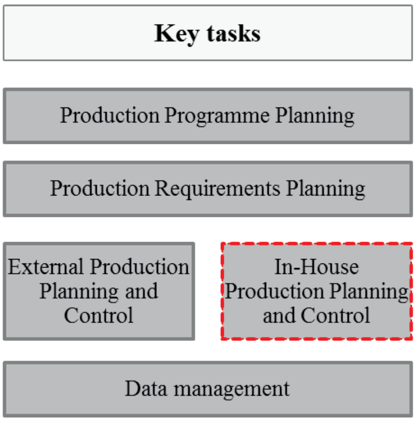


Figure 1. Key tasks of PPC with focus of this paper according to Luczak & Eversheim (1999).

This paper focuses on detailed scheduling in the context of in-house-production planning and control, which is often called just scheduling (Pinedo, 2008). This step typically determines a schedule, which comprises the exact dates for the start or end of operations and thus also the sequence of production orders. The detailed allocation of resources is also part of this planning step (Pinedo, 2008). Scheduling strategies can be differentiated into predictive, reactive, predictive-reactive as well as proactive ones (van Brackel, 2009). Predictive scheduling strategies create schedules before the beginning of the production process (van Brackel, 2009). They once create a schedule under the assumption of a deterministic production system. Reactive scheduling strategies do not create schedules as defined in common terms (Sabuncuoglu & Karabuk, 1999). They control the process locally, often using priority rules (O'Donovan, Uzsoy & McKay, 1999). Predictive-reactive scheduling strategies create an initial schedule and then adopt it in iterations to occurring disturbances (O'Donovan, Uzsoy & McKay, 1999). Proactive scheduling strategies try to avoid rescheduling by creating robust schedules, which e.g. anticipate disturbances by inserting idle times, for example Szelke & Monostori (1999). Autonomous control methods in this context possess characteristics of reactive scheduling.

2.2. Autonomous control

Autonomous control methods enable coping with dynamics and complexity in the production process. They base on decentralized decision-making authority (Freitag, Herzog & Scholz-Reiter, 2004). Prevailing, autonomous control approaches focus on the usage of existing flexibility potentials in the production system for generating decision alternatives (Schuh, Gottschalk & Höhne, 2007). For that matter, parts or production orders decide autonomously on available alternative routes through the production system (Scholz-Reiter & Freitag, 2007b). Logistic objects interact with each other, exchange information, decide for themselves on this basis and execute their decisions (Scholz-Reiter & Freitag, 2007b). Simulation studies indicate that autonomous control methods are able to increase the logistic performance (Scholz-Reiter & Freitag, 2007b). Several autonomous control methods have already been developed within the Collaborative Research Centre 637 at the University of Bremen (Gierth, 2009; Windt, Becker, Jeken & Gelessus, 2010). A detailed classification of these methods is given by Windt *et al.* (2010). The following Table depicts the state of the art and classifies the methods based on the descriptions of Windt *et al.* (2010), Scholz-Reiter *et al.* (2010) and Schmidt *et al.* (2007). In general, these methods can be divided into rational methods, bounded rational (bio-analogue) methods and respective combinations of them (Scholz-Reiter, Böse, Jagalski & Windt, 2007a), whereas the latter have not yet been analysed quantitatively and therefore are not depicted explicitly in Table 2. While rational methods decide based on the anticipation of future system states, bio-analogue methods transfer the behaviour of natural systems like ants or honey bees to production control (Scholz-Reiter, Böse, Jagalski & Windt, 2007a).

Table 2. Autonomous control methods.

Method type	Method
Rational methods	DLRP Production
	Due date method
	Gentelligent parts
	Link-state internet routing protocol
	One logistics target per rule
	Simple rule based 1 / Queue Length Estimator
	Simple rule based 2
Bounded rational (bio-analogue) methods	Ant algorithm/ Cunning ant algorithm
	Bacterial Chemotaxis
	Bee foraging
	Bionic manufacturing system
	Holonic Manufacturing
	Market based control

2.3. Order release and generation

According to Wiendahl (1997), the primary task of production control is the realisation of the production plan despite of potential disturbances. Kurbel (2005) thereby defines the order release as connector between production planning and control. The task of order release determines the point of time, from which on the production is authorized to start the processing of an order. It usually triggers the material supply and the assignment of material to a specific production order (Lödding, 2013). Order release thus has a significant impact on the logistic performance of a production system (Qi, Sivakumar & Gershwin, 2009; Wein & Chevalier, 1992).

There are several frameworks for the description and classification of order release methods in literature (Bergamaschi, Cigolini, Perona & Portioli, 1997; Lödding, 2013; Sabuncuoglu & Karapinar, 1999). According to Lödding (2013), release methods are divided into the classes of immediate order release, due date based order release, WIP regulating order release and approaches with workstation specific load balance as depicted in Figure 2. Classes of order release according to Lödding (2013)..

The order release function processes only orders, which are provided by the precedent order generation function. The order generation function creates production orders out of customer orders, material withdrawals or a production program. It determines the planned input into the production, the planned sequence and the planned output. In general, order generation methods can be classified as depicted in Figure 3. Classification criteria for order generation methods according to Lödding (2013). by the generation scope, trigger logic, the method character and the primary generation criterion, which is mainly individual for every method. (Lödding, 2013)

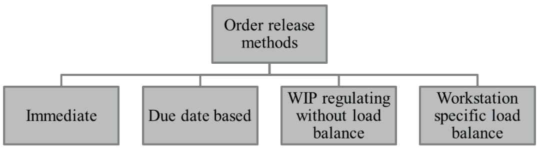


Figure 2. Classes of order release according to Lödding (2013).

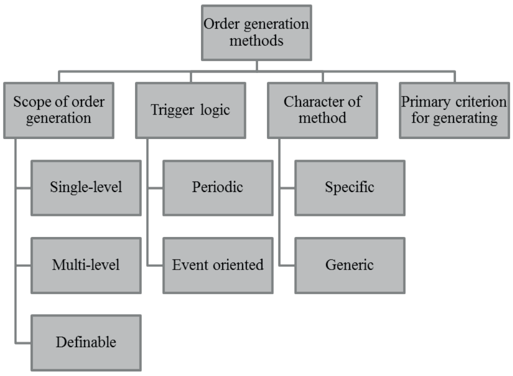


Figure 3. Classification criteria for order generation methods according to Lödding (2013).

2.4. Summarising basic relationships

The traditional function of production control is to realise the production plan also under – potentially unavoidable – disruptions (Wiendahl, von Cieminski & Wiendahl, 2005). A basic model of production control according to Lödding (2013) is shown in Figure 4. The model consists of four basic elements: the production control functions, the manipulated variables, the observed variables and the logistic objectives. The connections between the elements indicate causal relationships. The functions determine the manipulated variables in the way of the directions. The observed variables result from the deviation of two manipulated variables. The observed variables determine the degree of logistic objective achievement. Hence, the four functions of production control – order generation, order release, sequencing and capacity control – directly influence the degree of logistic objective achievement. Using autonomous control methods, they fulfil the sequencing task and thus, influence the logistic objectives. Throughput time is the length of time between the order›s release and the end of its processing. WIP level is a measure for released orders which have not yet been finished. WIP can be counted either in number of orders or in

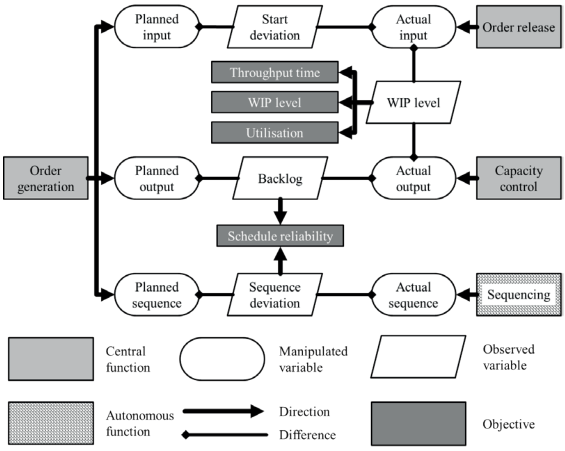


Figure 4. Production control model according to Lödding (2013).

time units. Utilisation describes the ratio of the mean and maximum possible output rate of a workstation. Finally, schedule reliability refers to the percentage of orders delivered within a defined delivery reliability tolerance. Lödding (2013)

3. Coupling order release and autonomous control methods

3.1. Theoretical evaluation

A theoretical evaluation is carried out in Table 3. Evaluation matrix of autonomous control methods and order release methods.. The evaluation considers selections of autonomous control methods and order release methods and examines the possibility of a combined application based on each method´s description in the corresponding reference. The methods are clustered within method types according to the classifications given in section 2. The character (●) represents a possible combination. However, the possibility of a combination does not coercively imply reasonability. The reasonability of a combined usage depends on each production system and its requirements. For example, the due date oriented order release can be combined with all autonomous control methods. If a company prioritises high due date reliability then a due-date oriented autonomous control method such as the DD method is more reasonable than a method such as SRB1/QLE which aims at minimising makespan and disregards due dates. The character (◑) indicates a possible combination under the prerequisite of an adaption of either the control or the release method. For instance, the Workload Control (WLC) method considers orders to be processed on a work centre for the workload calculation. However, autonomous control methods decide their route during run-time, so that adequate forecasting methods must be applied to combine these methods efficiently. Therefore, the evaluation in this case is at (◑). An evaluation of (○) indicates an impossible combination. For instance, the “G_POLCA”-method is based on product authorisation cards to control the number of jobs in production. The “DLRP”-method is based on collaborating intelligent products. These two methods are obviously impossible to combine. The asterisks (*) mark couples which are considered in the context of the simulation in section 3.2. Furthermore, compared to Table 1, the evaluation only considers autonomous control methods, which are described detailed enough to be reproducible. It is also apparent, that up to now, WIP regulating approaches and approaches with load balance cannot be combined with autonomous control methods without adaptions.

Therefore, adaptions, respectively adaption methods must be developed if a combined application of these methods is desired. Table 3. Evaluation matrix of autonomous control methods and order release methods. also indicates, that it depends primarily on the characteristics and requirements of each order release method, whether the combination is possible or not. This dependency reveals itself reading the Table line by line: If an order release method can be combined with one autonomous control method, it can also be combined with all others (except the SLRD method). The most frequent reason for incompatible combinations is that certain order release methods rely on the anticipation of future system states, for example as the WLC explained above. Thereby, in most cases they presume a deterministic production plan. Autonomous control methods, in contrast, decide during run-time. Therefore, as long as no dynamic and unpredicted events occur (e.g. rush orders, breakdowns), all autonomous control methods can be combined with all order release methods. But as this assumption is far from reality, the evaluation is often at (◑) for these cases. Besides, applying autonomous control methods is not reasonable under such static and deterministic conditions (cf. 2.1).

3.2. Simulation study

In order to corroborate the interdependencies of a combined application of order release and autonomous control methods, a simulation study was carried out as described in the following. The study picks up all combinations marked with a (*) in Table 3. Evaluation matrix of autonomous control methods and order release methods. to exemplarily show the degree of interdependency and the potential benefits of combined application. These combinations consider at least one method of each category, if the combination is possible without adaptions. The simulation study is based on a 3×3-machine model depicted in Figure 5, which is often used for the evaluation of autonomous control methods (de Beer, 2008; Scholz-Reiter, Jagalski & Bendul, 2008). For matters of comparability we orient the simulation study to a great extent on de Beer (2008), who examines the dynamics of production systems applying autonomous control methods.

Table 3. Evaluation matrix of autonomous control methods and order release methods.

Method type				Rational methods				Bounded rational methods / Bio-analogue methods				
	Reference			Scholz-Reiter, Jagalski & Bendul (2008)	Scholz-Reiter, Freitag, de Beer & Jagalski (2006)	Windt, Becker, Jeken & Gelessus (2010)	Rekersbrink, (2012)	Cicirello & Smith (2001); Windt *et al.* (2010)	Tsutsui & Liu (2007); Windt *et al.* (2010)	Armbruster *et al.* (2006); Windt *et al.* (2010)	Scholz-Reiter, Jagalski & Bendul (2008)	Scholz-Reiter, Görges, Jagalski & Naujok (2010)
		Method		Simple rule based 1 / Queue Length Estimator	Simple rule based 2	Due Date method	DLRP Production	Ant algorithm	Cunning ant algorithm	Pheromone approach	Bee foraging	Bacterial Chemotaxis
			Code	SRB1 / QLE	SRB2	DD	DLRP	ANT	C-Ant	PHE	BEE	CHE
Immediate order release	Lödding (2013)	Immediate order release	IMR	●*	●	●*	●	●	●	●*	●	●
Due date based order release	Thürer, Stevenson, Silva, Land & Fredendall (2012)	Periodic	PERIOD	●	●	●	●	●	●	●	●	●
	Lödding (2013)	Due Date oriented order release	DATE	●*	●	●*	●	●	●	●*	●	●
WIP regulating approach without load-orientation	Thürer, Stevenson, Silva, Land & Fredendall (2012)	Constant Work in Process	CONWIP	●*	●	●*	●	●	●	●*	●	●
	Qi, Sivakumar & Gershwin (2009)	WIPLOAD Control	WIPLOAD	●	●	●	●	●	●	●	●	●
	Fernandes & Carmo-Silva (2011)	Similar set-up and Latest Release Date	SLRD	●	●	●	○	●	●	●	●	●
	Fernandes & Carmo-Silva (2006)	Generic Paired-Cell Overlapping Loops of Cards with Authorization	G_POLCA	◑	◑	◑	○	◑	◑	◑	◑	○
	Lödding (2001)	Decentral inventory oriented manufacturing control	Dec_BOA	◑	◑	◑	○	◑	◑	◑	◑	○
	Lödding (2013); Wein (1988)	Bottleneck control	BOT	●	●	●	●	●	●	●	●	●
Workstation specific load balance	Irastorza & Deane (1974)	Order release with linear programming	LP	◑	◑	◑	◑	◑	◑	◑	◑	◑
	Jendralski (1978)	Workload Control	WLC	◑	◑	◑	◑	◑	◑	◑	◑	○
	Bechte (1980); Wiendahl (1991)	Load-oriented order release	BOA	◑	◑	◑	◑	◑	◑	◑	◑	○
	Baykasoğlu & Göçken (2011); Melnyk & Ragatz (1989)	Aggregate workload trigger, work in the next queue selection	AGGWNQ	◑	◑	◑	◑	◑	◑	◑	◑	○
		Work centre workload trigger	WCWT	◑	◑	◑	◑	◑	◑	◑	◑	○
	Thürer, Stevenson, Silva, Land & Fredendall (2012)	Lancaster University Management School order release	LMUS COR	◑	◑	◑	◑	◑	◑	◑	◑	○
		Superfluous load avoidance release	SLAR	◑	◑	◑	◑	◑	◑	◑	◑	○
	Thürer, Filho & Stevenson (2013)	Idle Machine Rule	IdleMR	◑	◑	◑	◑	◑	◑	◑	◑	○
		Space control order release	SpaceOR	◑	◑	◑	◑	◑	◑	◑	◑	○
		Standard Rule	StandR	◑	◑	◑	◑	◑	◑	◑	◑	○
	Zozom, Hodgson, King, Weintraub & Cormier (2003)	Job Planner	JP	◑	◑	◑	◑	◑	◑	◑	◑	○
	Gentile & Rogers (2009)	Workload Control Machine Center	WLCMC	◑	◑	◑	◑	◑	◑	◑	◑	○
	Weng, Wu, Qi & Zheng (2008)	Multi-agent-based workload control for make-to-order manufacturing	MA_WLC	◑	◑	◑	◑	◑	◑	◑	◑	○

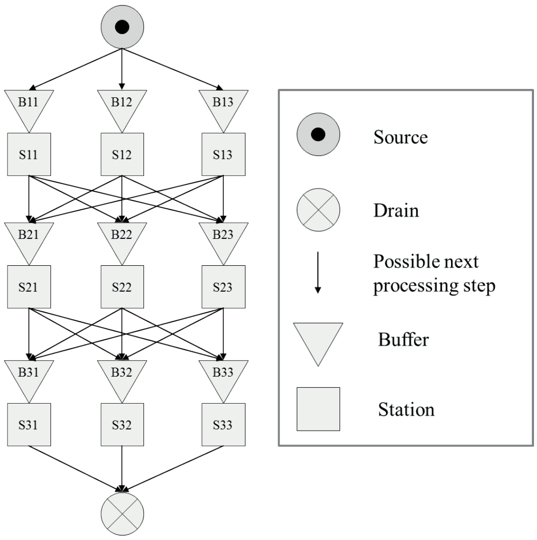


Figure 5. Basic model structure (de Beer, 2008, p.75).

Three product variants are produced (de Beer, 2008, p.84). Transportation times and set-up-times are included in the processing times, cf. de Beer (2008, p.84). The processing times depend on station and product according to Table 4 as in de Beer (2008, p.84).

Table 4. Machine and product dependent processing times (de Beer, 2008, p.84).

		Product A	Product B	Product C
1st stage	S11	2h	2.5h	3h
	S12	3h	2h	2.5h
	S13	2.5h	3h	2h
2nd stage	S21	2h	2.5h	3h
	S22	3h	2h	2.5h
	S23	2.5h	3h	2h
3rd stage	S31	2h	2.5h	3h
	S32	3h	2h	2.5h
	S33	2.5h	3h	2h

Each product has to be processed on one station at each stage (de Beer, 2008). de Beer (2008) disregards explicit breakdowns and models them by stochastic fluctuations of processing times of maximum 10%. This paper follows Scholz-Reiter *et al.* (2008) and Windt *et al.* (2010) by modelling explicit breakdowns, which increase both dynamics and uncertainty. To achieve a similar degree of dynamics as de Beer (2008), all stations are modelled with a failure rate of 10% and a deterministic mean-time-to-repair (MTTR) of 15 minutes. Based on the described set-up, several combinations of methods and input data are examined, as shown in Figure 6. Three data sets with increasing dynamics are combined with three order generation methods (cf. Table 5), three order release methods and three autonomous control methods (cf. Table 3). Concluding from Figure 6, 3^4=81 simulation scenarios are examined.

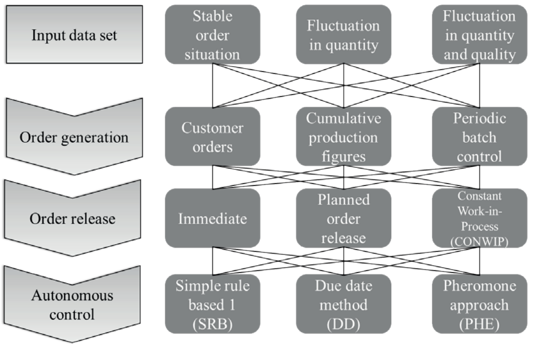


Figure 6. Considered methods and combinations.

Each input data set (i.e. order situation) comprises 5000 orders following Scholz-Reiter (2011). In general, we assume customer orders with given due dates. The order situations are depicted in Figure 7, Figure 8 and Figure 9. The sTable order situation contains almost no fluctuations concerning the demand quantity. All product variants have the same demand proportion. In this order situation, the same amount of each product type is manufactured every day.

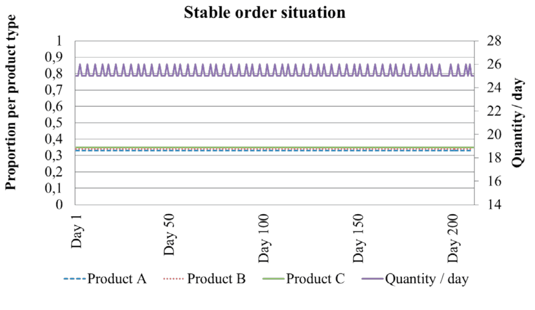


Figure 7. STable order situation.

The second data set comprises demand fluctuations concerning the demanded quantity. All product variants still have the same demand proportion. Therefore, this order situation contains higher dynamics than in the sTable order situation, but the product mix is the same.

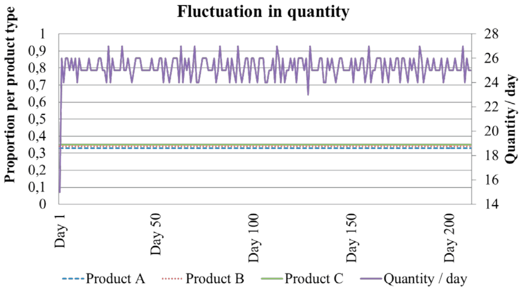


Figure 8. Fluctuation in quantity.

The third data set contains both fluctuations in quantity and quality, i.e. product variants. The product variants show an altering, periodic recurring demand proportion. The curve progression is similar to oscillating arrival. Thus, Figure 9 represents a very dynamic order situation with changing order volume and a changing product mix.

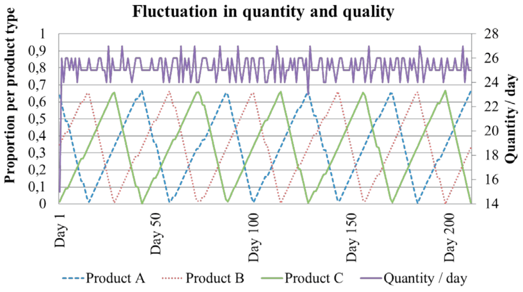


Figure 9. Fluctuation in quantity and quality.

These data sets represent customer orders, which are converted into production orders by the order generation methods. Three different order generation methods are considered in the simulation study in section 3. They are systematically chosen according to the classification criteria, as Table 5 indicates. The order release method according to the customer orders directly converts customer orders to production orders. The cumulative production figures method divides the production into control blocks and matches produced quantities with the production plan in a regular interval (Lödding, 2013). The method is implemented with the whole production as one control block and a daily matching of produced quantities. The periodic batch control method is implemented to release orders in a rolling horizon of a 6-day period. This is consistent with a weekly planning period, so that at the beginning of each week all orders for this week plus the first working day of the following week are immediately generated.

Table 5. Selection of order generation methods, cf. Lödding (2013).

Generation method	Scope of order generation	Trigger logic	Character of method	Primary criterion for generating
Customer orders	Single-level	Event oriented	Specific	Date and time
Cumulative production figures	Definable	Event oriented	Generic	Definable
Periodic batch control	Single-level	Periodic	Specific	Date and time

Finally, parameters for the CONWIP order release method and for the PHE control approach have to be defined before the simulation. CONWIP is implemented for a maximum load of 27 orders in the shop. With uniformly distributed orders in a 3x3 machine-model, a CONWIP of 27 causes 3 orders per station in average with 2 orders in queue. An existing queue is necessary to efficiently make use of methods like the SRB1 or DD method, so that 27 orders are an adequate parameterisation. The Pheromone approach uses a pheromone length of 5 orders as suggested by Armbruster *et al.* (2006).

3.3. Results

The simulation results depending on applied order release methods and data sets are summarised in Table 6. The values are averaged both over the three considered autonomous control methods and order generation methods depending on the order release method. The best value per order situation and logistic objective is highlighted.

Table 6. Averaged results dependent on order release method.

		Immediate order release	Planned order release	CONWIP
STable order situation	Due date reliability	0,479	0,228	0,131
	WIP (pcs.)	99,26	50,00	18,55
	Utilisation	0,929	0,902	0,898
	Average throughput time [h:mm:ss]	111:27:00	55:10:00	19:42
Quantity fluctuation	Due date reliability	0,568	0,122	0,533
	WIP (pcs.)	238,23	247,04	20,66
	Utilisation	0,852	0,830	0,822
	Average through-put time [h:mm:ss]	381:52:00	399:06:00	26:30:00
Fluctuation in quantity and quality	Due date reliability	0,011	0,112	0,110
	WIP (pcs.)	21,75	192,9	19,02
	Utilisation	0,819	0,853	0,851
	Average throughput time [h:mm:ss]	29:02:00	271:48:00	22:59

The Table indicates that there is no dominant order release method, i.e. different order release methods achieve considerable better values than others, but every method achieves at least two best values. Especially the throughput time reveals room for improvement e.g. comparing CONWIP to immediate order release. It is consequentially, that CONWIP achieves the best results both in WIP and in throughput time due to the direct relationship between those logistic objectives (Nyhuis & Wiendahl, 2008). The immediate order release disregards the WIP level and thus causes higher WIP and throughput time in all examined cases. Concerning the relationship between utilisation and WIP, it is noticeable, that the increase of 3% utilisation from CONWIP to immediate order release quintuples the WIP in the sTable order situation and approximately decuples the WIP in the order situation with fluctuations in quantity. This is consistent with the Funnel Model, compare Nyhuis & Wiendahl (2008): The utilisation increases slowly with disproportionately rising throughput time at high level of utilisation. The higher WIP level also causes an excessive increase in throughput time. The immediate order release achieves the best results in the first two data sets concerning the due date reliability. This is logical, because the other two order release methods keep back known orders, while the immediate order release method releases the orders considerably earlier. Nevertheless, the high due date reliability of the immediate order release method goes along with high WIP and throughput time. Regarding the due date reliability with fluctuation in quantity and quality, the planned order release performs best. Also CONWIP performs considerably better than the immediate order release method in this case. These results can be explained via the load balancing of these two methods. By smoothing the fluctuations a higher overall utilisation can be achieved by a homogenous distribution of orders onto stations. Thus, the due date reliability can be improved. However, it seems counterintuitive that in the most dynamic situation, the planned order release achieves the highest due date reliability. Taking into account the high WIP in this case, it is explainable that the plan causes high WIP, so that autonomous control methods have long queues for the calculation and many decision alternatives. Therefore, for the price of high WIP an increase of due date reliability is possible. Nevertheless, the best value of 11% is still deficient. This relationship between WIP and due date reliability is not a general one. Comparing these two performance indicators between CONWIP and immediate order release with fluctuations in quantity and quality, it is noTable that CONWIP achieves both a better due date reliability and lower WIP with also a higher utilisation. This can be explained via the specific characteristics of the autonomous control methods. Table 6 comprises average values which vary depending on the applied autonomous control methods. This is exemplarily depicted in Figure 10 and Figure 11. They illustrate the due date reliability for different data sets and for different combinations of order release methods and autonomous control methods.

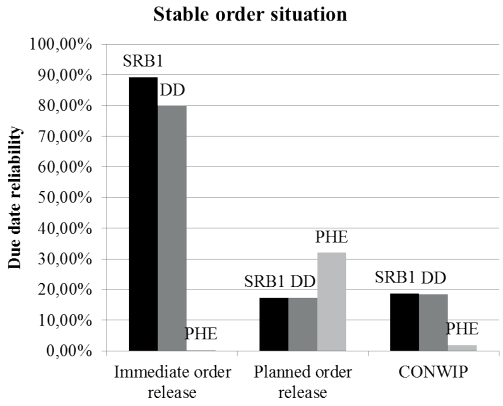


Figure 10. Due date reliability in sTable order situation.

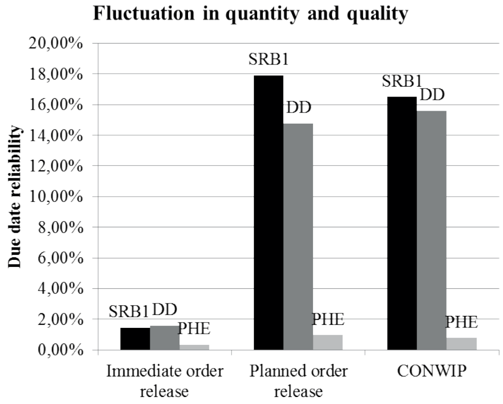
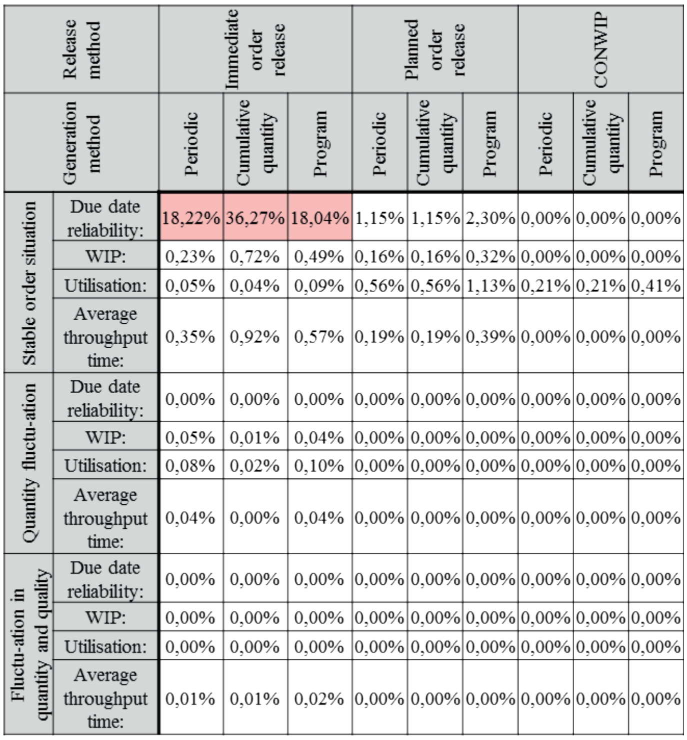


Figure 11. Due date reliability with fluctuation in quantity and quality.

Apparently, different combinations perform considerably better in different order situations. Especially in dynamic situations order release methods other than immediate release achieve significant better results. As explained above, smoothing the fluctuations enables a higher overall utilisation and improves the due date reliability by a homogenous distribution of orders onto stations. Thereby, especially due date oriented and queue-length oriented methods (SRB 1, DD) can prove their potential. The PHE method performs worst of all three considered methods because it reacts very slowly, especially in case of multiple variants. In this case, the PHE method uses the throughput time of the last 5 orders of the same product type on the corresponding station to decide, on which station to be processed. Thereby, deviations of processing times and queue length are considered and taken into account in decision making. However, if certain product types have not been produced for a longer time, e.g. due to demand fluctuations, throughput time information is out of date. Therefore, the quality of decision making generally decreases with a higher number of product variants applying the PHE method. This disadvantage could for instance be compensated by also taking into account the throughput time of other product variants and calculating the ration between the expected throughput time and measured throughput time.

The last aspect to examine is the impact of order generation methods. By building the average over order release methods, Table 6 implicitly assumes that the impact of order generation methods can be disregarded. Therefore, Figure 12 examines the absolute deviation from averaged values of performance indicators depending on the order generation method. It represents a comparison with Table 6. Only 3 out of 108 values show a deviation of more than 5 % with an average deviation of 0,79 % and a standard deviation of 4,23 %. These findings justify the assumption, that the effects of order generation are significantly softened by the following order release method. Thus, the focus on order release is justifiable.

The performance of the considered methods allows several conclusions for matching order release methods and autonomous control methods. As far as order release methods are concerned, CONWIP is recommended in combination with autonomous control methods in rather dynamic situations if low WIP and short throughput times are focussed. High due date reliability can be achieved with planned order release even in dynamic situations. However, the plan was scheduled with inserted idle times, so that it was robust towards the occurring dynamics. The immediate order release in combination with autonomous control methods is advantageous concerning utilisation in less dynamic order situations. Nevertheless, the efficiency of both order release methods and autonomous control methods strongly depends on the current order situation, logistic targets and further properties of the production system so that the overall suitability must be evaluated in each particular case.



Release method		Immediate order release			Planned order release			CONWIP		
	Generation method	Periodic	Cumulative quantity	Program	Periodic	Cumulative quantity	Program	Periodic	Cumulative quantity	Program
Stable order situation	Due date reliability:	18,22%	36,27%	18,04%	1,15%	1,15%	2,30%	0,00%	0,00%	0,00%
	WIP:	0,23%	0,72%	0,49%	0,16%	0,16%	0,32%	0,00%	0,00%	0,00%
	Utilisation:	0,05%	0,04%	0,09%	0,56%	0,56%	1,13%	0,21%	0,21%	0,41%
	Average throughput time:	0,35%	0,92%	0,57%	0,19%	0,19%	0,39%	0,00%	0,00%	0,00%
Quantity fluctu-ation	Due date reliability:	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	WIP:	0,05%	0,01%	0,04%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Utilisation:	0,08%	0,02%	0,10%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Average throughput time:	0,04%	0,00%	0,04%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
Fluctu-ation in quantity and quality	Due date reliability:	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	WIP:	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Utilisation:	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	Average throughput time:	0,01%	0,01%	0,02%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%

Figure 12. Absolute deviation from average values depending on order generation methods.

4. Conclusions

Production planning and control (PPC) has to cope with increasing complexity, dynamics and uncertainty (Kim & Duffie, 2004; Westphal, 2001). Autonomous control methods are considered as a promising approach for coping with these challenges (Scholz-Reiter & Freitag, 2007b). However, the effect of order release methods on the efficiency of autonomous control methods has not yet been examined. This paper provides a theoretic analysis of feasible method combinations. Furthermore, simulations confirm the high influence of the order release function on autonomous control methods. The results further revealed that the effects of order generation methods are softened by order release methods, so that for future research the assumption is justifiable to initially focus on combining order release with autonomous control. The differences of several autonomous control methods concerning the logistic objectives also reveal that more extensive studies need to be carried out to evaluate the suitability of combinations for different production systems. There is a broad consensus, that there is no universal dominant release method, respectively control method. The efficiency of both order release methods and autonomous control methods strongly depends on the current order situation, logistic targets and further properties of the production system. Users find a decision help in Table 3 to preselect method combinations for detailed evaluation. Future research must examine, which combinations of Table 3 are generally promising for which production system, and furthermore, which adaptions can be carried out to apply combinations of release methods and autonomous control methods of Table 3, which are currently not applicable. These adaptions concern especially the application of load balancing order release methods with autonomous control methods. Moreover, broadening the scope of research by approaches of capacity control is also field of future research.

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