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Understanding the Effect of Variation in a Production System

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Abstract

Variation is a root cause to waste in a production system because it creates interruptions in the production system. Variation is dissipating through the production flow and reduces productivity; therefore, to minimize the effect variations need to be handled with great care. In this research study it is examined how task starting time and duration is affected by variation. By simulating a sequence of work tasks using a normal distribution it has been possible to analyze variations' effect on task starting time, task durations, crew waiting time, etc. Ten simulation circles were simulated and analyzed. The analysis revealed that variation itself does not create waste. Waste is only emerging between handoffs, thus increased activity duration decreases the effect of variation. Moreover, by comparing a linear sequence and a network of activities, the effect of variation was found to depend on the design of the sequence.

Keywords:

Construction Management, Simulation, Variation, Waste, Workflow.

Introduction

Variation exists in many forms and is regarded as an enemy in a production system, when occurring variation can affect either the production flow or the product (González *et al.* 2010; Petersen 1999). Variation in the production flow decreases productivity (González *et al.* 2010) while variation in the product decreases quality and thereby increases the risk of errors and rework (Petersen 1999). In on-site construction, variation is part of everyday work (Thomas *et al.* 2003); therefore, variation needs to be managed.

In this research, focus is on variation in the duration of a scheduled task and the entailed variation in task starting time, both affecting the production flow. Variation is defined as the time difference between scheduled and actual in relation to duration and starting time (Wambeke *et al.* 2011). Completing an activity before deadline is defined as positive variation while completing and activity after deadline is defined as negative variation.

According to Hudghes et al. (2004) both negative and positive variation is creating chaos in the production system. While negative variation is creating delay (Howell and Ballard 1994) positive variation creates gaps in the production which most often result in unexploited capacity (Lindhard and Wandahl 2013; Yeo and Ning 2006). Thus, if the gaps of positive variation are exploited they could, in theory, counterbalance the effect of negative variation (Yeo and Ning 2006).

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A construction project consists of numerous of interdependent tasks which are creating a complex network of activities which need to be completed in a predefined sequence. Thus, variation in one activity will affect the subsequent activities (Wambeke *et al.* 2011).

The site management is in charge of a construction project their task is to make plans and schedules and to optimize the construction project as a whole, while a number of subcontractors execute a majority of the work tasks. Subcontractors tend to work on multiple construction projects simultaneously, the design of their contracts (unit price or lump sum) makes it important to make resource adjustments (labour, machinery, etc.) between projects to increase productivity (Sacks and Harel 2006). Therefore, despite the fact that variation can be transferred from one activity to the next the subcontractors on-site have a tendency to focus only on own work and even sometimes work towards own priorities without regarding how his work affects the rest of the construction project (Wambeke *et al.* 2011; Koskela and Howell 2001).

Koskela (1992) identifies variability, especially in relation to task length as an important root cause to why non-value adding activities emerge in on-site construction.

In addition Howell and Ballard (1994) find that by reducing inflow variation the production flow can be stabilized. From a scheduling perspective inflow variation is reduced when it is ensured that all scheduled activities are ready for completion (Ballard and Howell 1994).

Tommelein et al. (1999) illustrate, through the Parade Game, how variation affects the production. Han and Park (2011) later criticize the Parade Game for not allowing managers to interact. Han and Park (2011) point out that construction managers, during the production process, take actions to reduce the impact of variation, these actions often include schedule changes. Thus, the Parade Game does not create a realistic picture on how variation dissipates throughout the sequence.

Thomas et al. (2002) investigate the relationship between output variation and project performance but find no significant correlation between output variation and project performance. Instead the research reveals a close relationship between labour productivity and project performance. In a subsequent research Thomas et al. (2003) study the relationship between flow reliability and labour performance and find a strong correlation, the results are later supported by Gonzalez et al. (2008).

Wambeke et al. (2011) investigate the causes to variation in task duration and task starting time and find the top ten causes to be: ”(1) turnaround time from engineers when there is a question with a drawing; (2) completion of previous work;(3) obtaining required permits; (4) the quality of documents (errors in design and/or drawings); (5) rework; (6) socializing; (7) people arriving late and/or leaving early; (8) weather impacts; (9) lack of crew skills/experience; and (10) needing guidance/instruction from supervisor”.

Buffers are traditionally implemented, at strategic places in the production flow, to reduce the impact of variation and thus protect the production flow against uncertainties and to increase labour performance (Horman and Thomas 2005). According to Park and Peña-Mora (2004) traditional

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schedule buffering often fails. Moreover, Park and Peña-Mora (2004) find that by making buffers dynamic by continuous pooling, resizing, relocating, and re-characterizing the buffers the effect of the buffers will increase.

This research takes outset in Tommelein et al.'s (1999) Parade Game and illustrates what happens to variation if the production flow is changed. In the Parade Game bolts are passed through a production line consisting of a parade of subcontractors with subsequent tasks. Each subcontractor is dependent on the output (number of bolts passed on) from the previous subcontractor. Thus, production is regarded as a simple linear sequence, and not as a complex network of activities, in this factory-like process a number of identical bolts are passed through an assembly line. Length of activities vary, and the complexity of the activity network diagram creates interruptions to the parades. Moreover, only negative variation is considered. Finally, as pointed out by Han and Park (2011) managerial actions influence how variation is passed on through the scheduled sequence, but this is also the case for actions (i.e. resource adjustment) made by the subcontractors which according to Sacks and Harel (2006) are not made with interest to maximizing profit at the project but instead to maximizing profit at the individual company.

In this research study variation is monitored while changing the length of the tasks, and the impact of the scheduled design is investigated by comparing the effect of variation to respectively a linear and a network sequence. The sequences are shown in Figure 3. Management and subcontractor decisions are omitted from the simulations but their impact is discussed.

Methods

The production output from a small sequence of contractors is simulated by applying two different distributions: a random and a normal distribution. The distributions take outset in a normal six-sided dice, thus each production unit in the sequence can produce 1, 2, 3, 4, 5, or 6 units. Where the likelihood of a given productivity is determined by the distribution, see Table 1.

Table 1: The likelihood of output 1, 2, 3, 4, 5, or 6 at the random and normal distributions.

Output	Random distribution	Normal distribution
1	0.17	0.10
2	0.17	0.17
3	0.17	0.23
4	0.17	0.23
5	0.17	0.17
6	0.17	0.10

Based on the distribution patterns the output from each work day is simulated and summarized. A model is made in excel for 1 day, 6 days, and 36 days. With outset in the production mean 3.5 the target output from the tree simulations is respectively 3.5, 21, and 126. In the model the actual output is compared to the target and when reaching the target the delay in work days is calculated.

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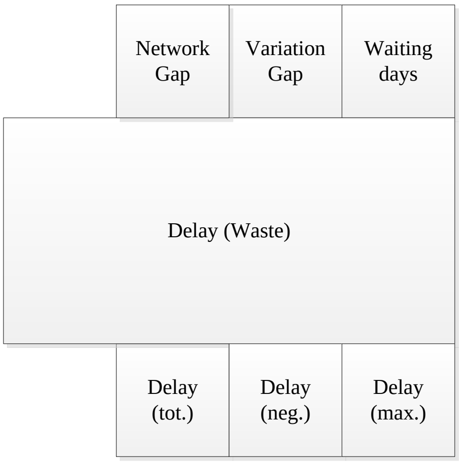

Figure 1: Model used for analyzing the simulated data.

Ten simulation cycles are calculated and afterwards analyzed. Figure 1 illustrates how the data is analyzed and an example is shown in Figure 2. The measurements stated in Figure 1 are explained below:

Network Gap:	Is gaps in the production caused by the interdependencies in the network of activities.
Variation Gap:	Is gaps in the production caused by positive variation
Waiting days:	Is waiting caused by delay in the system, the calculated waiting days is based on $delay_{neg}$.
$Delay_{tot}$:	Is delay caused by both positive and negative variation
$Delay_{neg}$:	Is delay caused by both positive and negative variation, but the production cannot be ahead of schedule (delay cannot be negative).
$Delay_{max}$:	Is only including negative delay and thus is a measurement of the maximum possible delay.

The results of the analysis can be found in Table 2, 3, 4, and 5.

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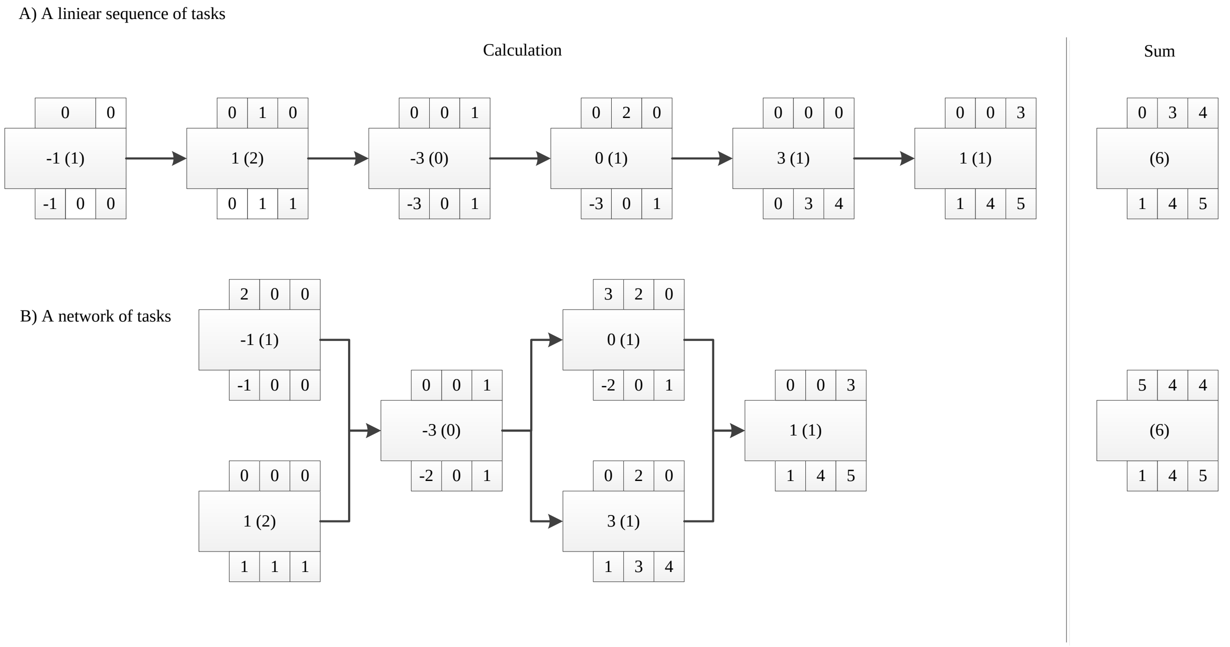

Figure 2: An example illustrating how the network gaps, variation gaps, waiting days, delay_{tot}, delay_{neg}, and delay_{max} are calculated.

Results

The Parade Game introduced by Tommelein et al. (1999) is a good instrument for illustrating how variation is passed on into the subsequent activities. In the presented research, variation is monitored while changing task length and it is investigated how network relations affect variation.

In on-site production one work crew is normally scheduled to begin when the crew before finishes. This is also the case in the simulation below where six work crews are completing six different work tasks. As illustrated in Figure 3, the work tasks can both be regarded as completed in a linear sequence or as a network of tasks.

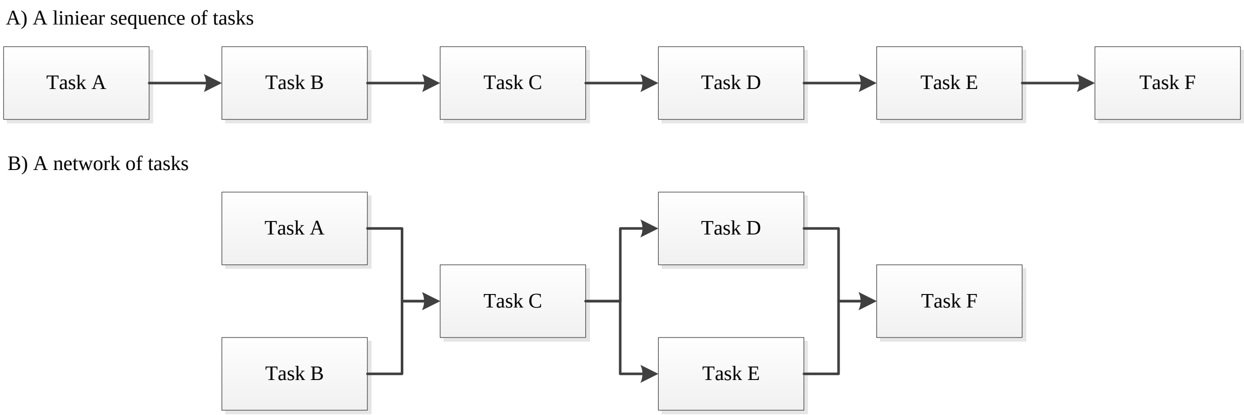

Figure 3: The work tasks can be arranged in multiple patterns. The following calculations are based on respectively the linear sequence (A) and the network (B).

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In Table 2 an even distribution is applied, as in the Parade Game, while a normal distribution is applied in Table 3. A normal distribution is most likely more close to the actual distribution patterns on-site. In a normal distribution it is more likely to receive values close to mean; thus, the normal deviation is more narrow than the evenly distribution. This possibly affects both waste and delay.

In Table 2 and Table 3, the task length is set to 1 work day which corresponds to a defined output at 3.5 which equals the production mean. The production output is natural numbers varying from one to six. Ten simulation circles were calculated of each distribution.

Table 2: Positive or negative variation accumulated after 1 work day. A started workday is fully included, rest productivity (waste) is noted in brackets. A refers to the linear sequence and B refers to a network of activities, see Figure 3.

Evenly distribution (random natural numbers from 1-6), Mean =3.5													
Circle		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Abs. Average [1]**	**Std. deviation**
Work crew A		1(3.5)	1(3.5)	1(1.5)	0(1.5)	0(1.5)	1(0.5)	0(2.5)	3(4.5)	1(5.5)	1(3.5)		
Work crew B		0(1.5)	0(2.5)	0(0.5)	0(2.5)	1(1.5)	1(4.5)	2(3.5)	1(0.5)	0(2.5)	1(4.5)		
Work crew C		0(0.5)	1(4.5)	1(2.5)	0(1.5)	0(1.5)	0(2.5)	0(1.5)	1(0.5)	1(0.5)	0(0.5)		
Work crew D		1(0.5)	0(0.5)	2(1.5)	0(0.5)	0(1.5)	2(3.5)	1(2.5)	2(1.5)	0(1.5)	1(3.5)		
Work crew E		0(0.5)	0(2.5)	2(5.5)	1(1.5)	2(1.5)	0(2.5)	1(1.5)	1(2.5)	0(2.5)	0(0.5)		
Work crew F		0(0.5)	1(3.5)	1(3.5)	1(2.5)	2(1.5)	2(1.5)	1(1.5)	0(1.5)	1(1.5)	1(2.5)		
Waste		7	17	15	10	11	15	13	19	14	15	13.6	3.50
Network Gaps	**A**	0	0	0	0	0	0	0	0	0	0	0	0
	B	2	1	1	1	3	2	2	3	1	1	1.7	0.82
Variation Gaps	**A**	0	0	0	0	0	0	0	0	0	0	0	0
	B	0	0	0	0	0	0	0	0	0	0	0	0
Waiting days	**A**	7	8	14	1	6	13	11	27	8	11	10.6	6.88
	B	5	7	9	1	6	6	9	17	7	5	7.2	4.13
Delay$_{tot}$	**A**	2	3	7	2	5	6	5	8	3	4	4.5	2.07
	B	2	3	5	2	5	5	4	6	3	3	3.8	1.40
Delay$_{neg}$	**A**	2	3	7	2	5	6	5	8	3	4	4.5	2.07
	B	2	3	5	2	5	5	4	6	3	3	3.8	1.40
Delay$_{max}$	**A**	2	3	7	2	5	6	5	8	3	4	4.5	2.07
	B	2	3	5	2	5	5	4	6	3	3	3.8	1.40
Delay$_{tot}$ / day	**A**	2	3	7	2	5	6	5	8	3	4	4.5	2.07
	B	2	3	5	2	5	5	4	6	3	3	3.8	1.40
Delay$_{neg}$ / day	**A**	2	3	7	2	5	6	5	8	3	4	4.5	2.07
	B	2	3	5	2	5	5	4	6	3	3	3.8	1.40
Delay$_{max}$ / day	**A**	2	3	7	2	5	6	5	8	3	4	4.5	2.07
	B	2	3	5	2	5	5	4	6	3	3	3.8	1.40

Table 3: Positive or negative variation accumulated after 1 work day. A started workday is fully included, rest productivity (waste) is noted in brackets. A refers to the linear sequence and B refers to a network of activities, see Figure 3.

Normal distributed (natural numbers from 1-6), Mean = 3.5; Std. deviation = 1.87

[1] Abs. Average is the average of the absolute values thus it is the average "distance" from zero.

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Circle		1	2	3	4	5	6	7	8	9	10	Abs. Average	Std. deviation
Work crew A		0(0.5)	1(1.5)	0(1.5)	0(0.5)	0(2.5)	1(3.5)	0(1.5)	0(0.5)	1(1.5)	1(5.5)		
Work crew B		1(2.5)	0(0.5)	0(0.5)	0(0.5)	1(0.5)	0(0.5)	1(1.5)	1(2.5)	1(3.5)	0(1.5)		
Work crew C		0(0.5)	0(1.5)	0(1.5)	1(1.5)	0(0.5)	0(0.5)	0(2.5)	0(0.5)	0(0.5)	1(2.5)		
Work crew D		0(1.5)	1(4.5)	0(2.5)	1(0.5)	0(1.5)	0(1.5)	0(0.5)	0(1.5)	0(1.5)	0(2.5)		
Work crew E		2(0.5)	1(3.5)	1(2.5)	0(1.5)	0(1.5)	0(0.5)	1(3.5)	1(4.5)	1(4.5)	1(2.5)		
Work crew F		0(0.5)	1(3.5)	0(1.5)	0(1.5)	1(2.5)	0(1.5)	0(2.5)	1(1.5)	1(2.5)	0(2.5)		
Waste		6	15	10	6	9	8	12	11	14	15	10.6	3.41
Network Gaps	**A**	0	0	0	0	0	0	0	0	0	0	0	0
	B	3	1	1	1	1	1	2	2	1	2	1.5	0.71
Variation Gaps	**A**	0	0	0	0	0	0	0	0	0	0	0	0
	B	0	0	0	0	0	0	0	0	0	0	0	0
Waiting days	**A**	6	8	1	5	4	5	5	5	10	9	5.8	2.62
	B	6	5	1	4	4	4	5	5	5	8	4.7	1.77
Delay$_{tot}$	**A**	3	4	1	2	2	1	2	3	4	3	2.5	1.08
	B	3	3	1	2	2	1	2	3	3	3	2.3	0.82
Delay$_{neg}$	**A**	3	4	1	2	2	1	2	3	4	3	2.5	1.08
	B	3	3	1	2	2	1	2	3	3	3	2.3	0.82
Delay$_{max}$	**A**	3	4	1	2	2	1	2	3	4	3	2.5	1.08
	B	3	3	1	2	2	1	2	3	3	3	2.3	0.82
Delay$_{tot}$ / day	**A**	3	4	1	2	2	1	2	3	4	3	2.5	1.08
	B	3	3	1	2	2	1	2	3	3	3	2.3	0.82
Delay$_{neg}$ / day	**A**	3	4	1	2	2	1	2	3	4	3	2.5	1.08
	B	3	3	1	2	2	1	2	3	3	3	2.3	0.82
Delay$_{max}$ / day	**A**	3	4	1	2	2	1	2	3	4	3	2.5	1.08
	B	3	3	1	2	2	1	2	3	3	3	2.3	0.82

After ten simulations the normal distribution shows a remarkable decreased delay compared to the random distribution. The difference in delay is expected because a normal distribution has a decreased likelihood of taking upper or lower values and thus having a decreased std. deviation. Due to the calculation principles, where rest capacity of a started work day is fully included, positive variation cannot occur, as seen in the simulation in Table 2 and Table 3, when only regarding one singular work day.

Waiting days are caused by delay transmitted through the sequence. The correlation between waste and waiting days is distinct when the results are compared. Thus, by decreasing delay the number of waiting days is decreased. It is important to be aware that the simulation does not include managerial actions to reduce the effect of variation.

The simulation also showed a minor decrease in waste. The decrease in waste can either be a coincidence or can be due to the difference in distribution patterns but more simulations are needed in order to make any conclusions.

A comparison between the linear sequence and the network reveals a minor difference in delay with favour to the network. Despite the reduced delay, the complexity of the network causes small un-exploitable gaps to emerge, this due to the difference in task length in parallel work tasks.

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Finally, it is clear from the simulations that variation is not by itself creating waste. Waste is only emerging between handoffs. Thus, by reducing the number of handoffs, compared to the Parade Game, the waste is drastically reduced.

The change to a normal distribution was chosen to create a more realistic picture of variation. Normally on-site production will not consist of activities with only one singular work day but instead include a number of work days. In Table 4 it is shown what happens when the number of work days between handovers is increased to six. Even though the negative delay and the std. deviation are increased the delay per work day is drastically decreased.

Table 4: Positive or negative delay accumulated after 6 work days. Production could vary between 1-6 with a predicted average at 3.5. A started workday is fully included.

Normal distributed (natural numbers from 1-6), Mean = 3.5; Std. deviation = 1.87													
Circle		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Abs. Average[1]**	**Std. deviation**
Work crew A		0(2)	1(0)	0(0)	3(4)	0(0)	1(1)	2(2)	1(0)	1(2)	1(3)		
Work crew B		1(2)	1(0)	-1(0)	0(0)	2(3)	0(5)	2(2)	0(1)	2(4)	-1(1)		
Work crew C		2(3)	-1(1)	0(3)	1(0)	2(0)	-1(0)	1(5)	1(2)	1(0)	0(4)		
Work crew D		0(1)	1(3)	0(0)	0(2)	-1(1)	0(0)	-1(1)	1(0)	-1(2)	-1(0)		
Work crew E		-1(0)	2(3)	1(1)	0(0)	0(0)	-1(1)	0(3)	0(3)	3(2)	0(2)		
Work crew F		-2(1)	3(1)	-1(1)	-1(0)	-1(1)	1(0)	0(1)	0(2)	0(2)	1(4)		
Waste		9	8	5	6	5	7	14	8	12	14	8.8	3.43
Network Gaps	**A**	0	0	0	0	0	0	0	0	0	0	0	0
	B	2	1	2	3	3	2	1	2	5	3	2.4	1.17
Variation Gaps	**A**	0	0	1	0	0	1	0	0	0	1	0.3	0.44
	B	0	0	0	0	0	0	0	0	0	0	0	0
Waiting days	**A**	9	10	1	18	12	2	19	10	17	1	9.9	6.87
	B	10	3	1	15	14	1	11	8	14	4	8.1	5.51
Delay$_{tot}$	**A**	0	7	-1	3	2	0	4	3	6	0	2.4	2.72
	B	1	5	0	3	3	1	3	3	6	2	2.7	1.83
Delay$_{neg}$	**A**	0	7	0	3	2	1	4	3	6	1	2.7	2.41
	B	1	5	0	3	3	1	3	3	6	2	2.7	1.83
Delay$_{max}$	**A**	3	8	1	4	4	2	5	3	7	2	3.9	2.23
	B	1	6	1	4	4	2	3	3	6	2	3.2	1.81
Delay$_{tot}$ / day	**A**	0.00	1.17	-0.17	0.50	0.33	0.00	0.67	0.50	1.00	0.00	0.43	0.45
	B	0.17	0.83	0	0.5	0.5	0.17	0.5	0.5	1	0.33	0.45	0.30
Delay$_{neg}$ / day	**A**	0	1.17	0	0.5	0.33	0.17	0.67	0.5	1	0.17	0.45	0.40
	B	0.17	0.83	0	0.5	0.5	0.17	0.5	0.5	1	0.33	0.45	0.30
Delay$_{max}$ / day	**A**	0.50	1.33	0.17	0.67	0.67	0.33	0.83	0.50	1.17	0.33	0.65	0.37
	B	0.17	1	0.17	0.67	0.67	0.33	0.5	0.5	1	0.33	0.53	0.30

The results show a small reduction in waste, but it is considered only as a coincident and it is expected that the results will even out if the number of simulations are increased.

Moreover, two types of gaps emerge. Once again the network design introduces un-exploitable gaps, but this time positive variation causes exploitable "variation gaps" to emerge. Positive variation is resulting in activities being completed before the expected deadline. If negative variation exists in the production flow, the positive variation first has to counter balance the negative variation before the

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gaps emerge. A network reduces the likelihood for variation gaps; thus, when having parallel work tasks both tasks have to finish before deadline, i.e. the task with longest duration always determine the flow of the work. This is why negative variation is more easily transmitted than positive variation. It is a management task to ensure that “variation gaps” are exploited satisfactorily.

Three different delay measures are calculated. Delay$_{tot}$ is the delay including both positive and negative variation. Compared to the simulation with 1 work day the results with 6 days work task does only show a minor increase in delay$_{tot}$. Thus, the delay pr. day is drastically decreased. Delay$_{neg}$ allows positive delay to counter balance negative delay but additionally positive variation is not included. Thus, the production flow can never be ahead of time. Delay$_{neg}$ is corresponding to a situation where site management completely ignores the production flow. Compared to the simulation with 1 work day the delay is once again only showing a minor increase. Delay$_{max}$ is not considering positive variation, thus only negative variation is accumulated in the production flow. Compared to the simulation with 1 work day the 6 days simulation shows an increase in delay$_{max}$. The results might have been influenced by the fact that in the one day simulation no positive variation could occur, i.e. as in the delay$_{max}$ measurement. The simulation reveals small differences between linear (A) and network (B) especially at delay$_{max}$, but the number of simulation circles needs to be increased to draw any conclusions. Finally, the number of waiting days is slightly higher if a linear sequence is applied.

In theory negative variation would be outbalanced by positive variation. This despite that variation released onto the production flow will always cause waste appearing as gaps, waiting time, or delay. In the simulation a started work day is wasted, this will pull the result in a negative direction. The mentioned tendencies are confirmed by increasing the work days to 36, the result is showed in Table 5.

Table 5: Positive or negative delay accumulated after 36 work days. Production could vary between 1-6 with a predicted average at 3.5. A started workday is fully included.

Normal distributed (natural numbers from 1-6), Mean = 3.5; Std. deviation = 1.87													
Circle		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Abs. Average[1]**	**Std. deviation**
Work crew A		2(2)	-2(1)	-1(1)	2(1)	1(1)	-1(0)	-1(1)	1(1)	0(4)	-4(2)		
Work crew B		-1(4)	2(0)	1(2)	3(3)	2(1)	4(0)	-1(2)	-1(1)	-3(3)	2(0)		
Work crew C		-3(0)	3(1)	-3(1)	-1(0)	1(5)	-1(1)	-2(4)	1 (4)	-1(2)	3 (3)		
Work crew D		1(0)	-2(1)	-3(0)	-2(0)	2(3)	2(4)	1(2)	3(0)	-1(2)	3(3)		
Work crew E		1(4)	-3(0)	-1(4)	-4(3)	0(1)	2(5)	3(4)	4(0)	2(1)	1(4)		
Work crew F		2(1)	-4(1)	-2(0)	4(4)	1(2)	0(0)	1(1)	-1(0)	0(3)	1(1)		
Waste		11	4	8	11	13	10	14	6	15	13	10.5	3.57
Network Gaps	**A**	0	0	0	0	0	0	0	0	0	0	0	0
	B	3	5	4	3	3	5	2	3	6	8	4.2	1.81
Variation Gaps	**A**	2	2	7	2	0	1	4	0	5	4	2.7	2.26
	B	1	0	3	0	0	0	3	0	4	0	1.1	1.60
Waiting days	**A**	6	10	1	13	20	19	5	14	2	24	11.4	7.95
	B	3	15	1	7	13	15	3	11	2	20	9.0	6.68
Delay$_{tot}$	**A**	2	-6	-9	2	7	6	1	7	-3	6	1.3	5.66
	B	2	-1	-5	4	6	5	1	5	1	9	2.7	3.97
	A	4	0	0	4	7	7	5	7	2	10	4.6	3.27

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$Delay_{neg}$	**B**	3	0	0	4	6	5	4	5	2	9	3.8	2.74
$Delay_{max}$	**A**	6	5	1	9	7	8	5	9	2	10	6.2	3.01
	B	5	5	1	7	6	6	4	6	2	9	5.1	2.33
$Delay_{tot}$ / day	**A**	0.06	-0.17	-0.25	0.06	0.19	0.17	0.03	0.19	-0.08	0.17	0.14	0.16
	B	0.06	-0.03	-0.14	0.11	0.17	0.14	0.03	0.14	0.03	0.25	0.11	0.11
$Delay_{neg}$ / day	**A**	0.17	0.14	0.03	0.25	0.19	0.22	0.14	0.25	0.06	0.28	0.17	0.08
	B	0.08	0	0	0.11	0.17	0.14	0.11	0.14	0.06	0.25	0.11	0.08
$Delay_{max}$ / day	**A**	0.17	0.14	0.03	0.25	0.19	0.22	0.14	0.25	0.06	0.28	0.17	0.08
	B	0.14	0.14	0.03	0.19	0.17	0.17	0.11	0.17	0.06	0.25	0.14	0.06

The results show a small increase in waste; thus as suspected, the reduction observed in the previous simulation is a coincident.

It is confirmed that the likelihood of variation gaps is higher if the work tasks are arranged in a linear sequence. And it is moreover confirmed that a linear sequence has a higher risk of emerging waiting days. As previously stated managerial decisions but also the sequence have a major effect on waste (i.e. gaps, waiting, and delay). Thus, waste can be avoided if the work crew, experiencing a gap in the production flow or is forced to wait for a particular task to finish, can continue their work outside the sequence, this is supported by Lindhard and Wandahl (Lindhard and Wandahl 2012). Besides carefully selecting the best possible work sequence, buffering, overmanning, and overtime are managerial instruments which through a well considered usage are critical to successfully reduce the effect of variation (Han and Park 2011; Kog *et al.* 1999). Despite, site-management will compare actual progress with planned to reveal variability and if necessary take action (Rodrigues and Bowers 1996; Moselhi and El-Rayes 1993), these actions are not implemented in the simulation because intervention is depending on a site-manager's individual determination (Han and Park 2011). Finally, the actions of the subcontractors will also affect the results. Subcontractors tend to adjust resources between projects and work towards own priorities (Sacks and Harel 2006). Adjustments made by subcontractors can cause interruptions to the production flow. According to Hopp and Spearman (2000), the sub-optimization is resulting in prolonged cycle time and growing buffers, which surfaces as waiting time to the other contractors. The adjustments are depending on a lot of external factors such as production progress in parallel production projects and are impossible to forecast and therefore omitted from the simulation.

Like in the simulation using 6 days work task the linear sequence is revealing a huge difference between $delay_{tot}$ and $delay_{max}$. In both simulations the $delay_{tot}$ is lower and the $delay_{max}$ is higher if a linear sequence is selected. Mathematically it can be concluded that a linear sequence will never have a lower $delay_{max}$, because delay in a network can be divided between parallel activities.

The delay pr. work day is once again decreasing. The relationship is evident. By considering waste maximum (lowest difference) it takes with tasks of 1 work day 1.52 work day to be one average work day late. With tasks at a length of 36 work days it takes 21 work days to be one average work day late. Thus, if production is accelerated, besides the increased risk of variation, the shortening of the work task will increase the effect of (the increased) variation and thus putting pressure on site-

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management by increasing the risk of waste. Thus accelerating work output leads to reduced productivity (Hanna *et al.* 2005).

Conclusion

Variation has been well known for creating interruptions in a predefined production flow, interruptions which poses the ability to cause waste if the interruptions are note wisely managed. In the presented research, a simulation modeling variation in a production process has been presented. Even though focus has been on construction site the results can be applied to the production industry in general. By means of the simulation, it has been shown that variation is not itself creating waste and that waste only is emerging between handoffs. The longer duration an activity has the smaller is the effect of variation, because negative and positive variation will counter balance each other. Therefore, waste can be reduced for instance by compiling small work tasks into clusters or by reducing the number of trades on-site to reduce the number of handoffs. Moreover, it was found that waste can be hindered by ensuring that all work crews can continue their work, for instance with an out of sequences work task.

Moreover, the design of the production flow, i.e. the sequence, is found to have a great impact on the effect of variations, for instance does a network as shown introduce network gaps. Thus, by closely considering the sequence waste might be reduced.

In future research different and more complex network sequences could be examined to create a deeper understanding of how the effect of variation changes, and thus how variation can be managed. The presented study is based on 10 simulation circles; focus is on showing the actual numbers, because the actual numbers increases the depth and understanding to what happens. In future research the number of circles could be increased to allow hypothesis testing and other statistical analysis.

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