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Learning to see Value-Adding and Non-Value-Adding Work Time in Renovation Production Systems

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Abstract

For decades construction labour productivity has been stagnated or declining. Changing this issue requires new knowledge on the labour-intensive construction production system. The work sampling method was applied to collect data from 3 renovation construction production systems. It quantifies observations of on-site work and enables deep analyses of how time is used. The analysis revealed that the renovation projects had a baseline of value-adding-work (VAW) time on 29.5%. It further identified 5 system behaviours outlining how VAW and Non-Value-Adding work (NVAW) time behaves. The new knowledge of how both VAW and NVAW time behaves advances knowledge on how time is wasted in construction projects and opens new branches of future research. The findings are furthermore of potential use to industry professionals who work with process improvement in renovation projects because they provide, among others, answers to how targets can be defined for both VAW and NVAW.

Keywords
production system, behaviour, work sampling, direct work, waste, lean, renovation, refurbishment, improvement, management, productivity, TFV theory.

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1. Introduction

Onsite construction is labour-intensive. This is evident when looking at the labour cost which represents 40–60% of the total project costs (Buchan et al. 2006; Kazaz et al. 2008; Smith 2013), with renovation being even more labour-intensive than new build (Kazaz et al. 2008; Havelund 2013). The high need for labour in onsite construction combined with the fact that Construction Labour Productivity (CLP) has been stagnated or declining for years in most countries (Arditi and Mochtar 2000; Teicholz et al. 2001; Abdel-Wahab and Vogl 2011; Teicholz 2013; Nasir et al. 2014; Changali et al. 2015; WEF and BCG 2016; Ahmad et al. 2020), emphasises the need for further knowledge on how CLP can be increased.

Direct work (DW), the proportion of production time spent on value adding work, and CLP is known to be positively correlated on activity and project level (Thomas et al. 1984; Liou and Borcherding 1986; Olomolaiye et al. 1987; Handa and Abdalla 1989; Al-Ghamdi 1995; Kaming et al. 1997; Siriwardana et al. 2017) as well as on national level (Neve, Wandahl, Lindhard, et al. 2020). Thus, increasing onsite DW is one approach to change the current CLP development.

This research's objective is, from a production system perspective, to explore DW and non-value-adding work (NVAW) time. The purpose is to establish a deeper understanding of DW and NVAW time and their behaviour in a renovation production system. The aim is to close a knowledge gap on how both DW and NVAW time can be understood, identified, and seen. It is anticipated that an increased understanding of DW and NVAW time will support both industry and academia in their effort to increase DW and hereby CLP.

2. Background

The seminal work of Koskela (1992); Ballard and Howell (1998); Koskela (2000) introduced lean to construction, categorized construction as a production system, and introduced the transformation, flow and value (TFV) theory of construction production. The TFV theory provides the first coherent explanation of construction production as three interlinked perspectives supplementing each other, and all combined needed to understand and obtain successful construction projects.

The novel understanding of both the construction production system and lean in construction has also been used to develop suitable management methods (Ballard 2000) and to understand some of the inherent construction system behaviours as for example variability (Tommelein et al. 1999). The seminal work has shown that real improvements in construction requires a profound understanding of the production system. This research's overall objective is to increase time spent on DW in renovation projects by learning to see and understand DW and NVAW time. Thus, the background will describe the production system of interest, namely renovation, how analysis of construction production systems can be performed with different approaches, and the research gap and associated research questions.

2.1 Renovation production system

The construction production system of renovation projects distinguishes itself from other construction production systems by having several unique characteristics (Whiteman and Irwig 1988; Sanvido and Riggs 1991; CIRIA 1994; Egbu 1994; Krizek et al. 1996; Rahmat 1997; CII 2009). A significant characteristic distinguishing renovation from new build is the existing building structure (CIRIA 1994). The renovation production system, furthermore, often has to manage highly skilled or specialized work, e.g. the removal of asbestos hidden in the existing building structure, which, in itself, generate challenges for the management as they may need to interrupt the scheduled production flow (Bryde and Schulmeister 2012). Holm and Bröchner (2000) also point out that renovation work often includes work in occupied buildings. Tenants in proximity to ongoing construction work requires a high level of protection (e.g., dust, noise) and make the management of the craftsmen-tenant relationship an additional challenge in renovation. Further, Miller and Buys (2008) address the challenge of tenants opposed to the renovation caused by, among others, communication challenges.

These characteristics of renovation projects furnish a challenging environment to manage (Tzortzopoulos et al. 2020). Both the traditional project management approach (Sanvido and Riggs 1991; CIRIA 1994; Egbu 1994, 1995; Egbu et al. 1996; Krizek et al. 1996; Egbu 1997; Rahmat 1997; Egbu et al. 1998; Egbu 1999; McKim et al. 2000; Henrich 2009) and lean project management approach (Pereira and Cachadinha 2011; Bryde and Schulmeister 2012; Kemmer and Koskela 2012; Kemmer et al. 2013; Kemmer and Koskela 2014; Haarr and Drevland 2016; Kemmer et al. 2016; Vrijhoef 2016; Kemmer 2018) have been researched in renovation projects. Kemmer (2018) reviewed the literature and points out that the traditional project management approach is insufficient in renovation and argue that lean management is a superior approach. He argues that the traditional approach has a too narrow focus on transformations whereas lean expands the focus to cover both transformations, flow, and value. In the book chapter "Lean as an appropriate approach for managing production in renovation projects" (Tzortzopoulos et al. 2020), Kemmer and Koskela argue that: "*the compression of lead time (for the construction phase) and reduction of variability are the most powerful principles of production management for driving improvements in renovation*". The two principles are directly related to the concept of waste in construction production (Tommelein et al. 1999; Koskela 2000; Tzortzopoulos et al. 2020). Waste reduction have not yet concurred construction (Bølviken and Koskela 2016) because waste in construction is still a very abstract concept that needs further research (Tzortzopoulos et al. 2020).

2.2 Production system analyses

When analysing a production system in operations management, system behaviours as trends, seasonality, cycles, and variations are sought identified to enable identification of improvement areas or to enable forecasting (Stevenson 2011). In construction, previous research has analysed the production system behaviour, variability, to, among others, compress lead time (Tommelein et al. 1999; Gonzalez et al. 2008; Zegarra and Alarcón 2013; Lindhard 2014; Zegarra and Alarcón 2017; Abou-Ibrahim et al. 2019; Lindhard et al. 2019). Others have focused on delays in construction (Lindhard and Wandahl 2014; Zarei et al. 2018; Gunduz and Tehemar 2019) and how they can be mitigated (Arantes and Ferreira 2020). Zegarra and Alarcón (2019) goes in another direction and analyses system behaviours through the lenses of lean management and complexity theories. Process mapping with takt-time planning (Heinonen and Seppänen 2016; Lerche, Neve, Wandah, et al. 2020), location-based methods (Kenley and Seppänen 2010; Olivieri et al. 2018; Lerche, Neve, et al. 2019; Lerche, Seppänen, et al. 2019) and the Last Planner System (LPS) (Ballard 2000; Lerche, Neve, Ballard, et al. 2020) are other approaches used for production system analysis.

The WS method has additionally been used to analyse production systems from the perspective of how, for example, DW and NVAW time behaves during a day. The WS method uses direct observations, which are quantified by categorising observations into suitable categories fitting the work of interest. The method has been developed from using only the two categories of DW and NVAW, to now using multiple categories to further specify NVAW (Gong et al. 2011). The category of DW reveals how much of the possible production time is spend on value adding work. The remaining categories vary depending on the aim of the study. Dividing NVAW into subcategories enables a more detailed analysis of the WS data and hereby improved understanding of wasted time.

The WS method has been applied for decades (Gong et al. 2011) with multiple purposes as the following will show. Logcher and Collins (1978) used the WS method to understand how management impacts labour productivity. Thomas (1981) investigated how WS could lower construction costs. WS has further been used to create insights into how different factors affect labour productivity onsite (Horner et al. 1987). Winch and Carr (2001) used it to compare projects in two countries, and Allmon et al. (2000); Björkman et al. (2010); Gong et al. (2011) used it to study trends over time. WS data has further been used to help understand the effect labour movement has on overall project efficiency (Teizer et al. 2020).

Studies have also presented day curves based on WS data, revealing how both DW and NVAW behaves during a normal day of production (Björkman et al. 2010; CII 2010; Gouett 2010; Gouett et al. 2011; Shahtaheri 2012; Hajikazemi et al. 2017; Skovbogaard 2017; Hwang et al. 2018). The WS method has also been utilised as an integrated part of creating continuous improvements on construction projects (Gouett et al. 2011; Hwang et al. 2018; Neve, Wandahl, Lerche 2020).

One of the challenges of using the WS method is to understand which DW targets one should assign to different projects and trades. Research has discussed and proposed initial solutions to that challenge without any final answer (Gong et al. 2011; Shahtaheri et al. 2015). The problem of assigning DW targets is clear because large variances in DW rates occur between trades (Björkman et al. 2010; Kalsaas 2010; Josephson and Björkman 2013; Kumar et al. 2014; Shahtaheri et al. 2015; Sheikh 2016; Sheikh et al. 2017), and for similar trades within one project or across multiple projects (Logcher and Collins 1978; Thomas 1981; Olomolaiye et al. 1987; Handa and Abdalla 1989; Salim and Bernold 1994; Strandberg and Josephson 2005).

An area that has only been scarcely researched is how the WS method can be used to shed light NVAW tine in construction with Kalsaas (2010) and Kalsaas et al. (2014) being one of the few. Thus, much further research is needed to fully understand the potential of combing the WS method with NVAW time for the analysis of time in construction production.

3. Research objective, scope definition and research questions

Despite the importance, only little research has examined production system behaviours in renovation projects. As outlined in the introduction, close to 60% of the total project cost originates from labour expenses. Thus, improving time spent on DW will have a large effect on the economic performance of a project.

This research uses a novel approach to shed light on DW and NVAW. By applying the WS method the proportions of craftsmen's DW and NVAW time has been analysed using a flow view. The flow view is associated with the TFV theory of production by Koskela (2000) were the production resource is time (Bølviken et al. 2014). Koskela (2000) describes the flow view of production in five steps as outlined below:

1. *Conceptualization of production:* as a flow of materials composed of transformation, inspection, moving and waiting.
2. *Main principle:* elimination of waste (NVAW).
3. *Methods and practices:* continuous flow, pull, production control, continuous improvement.
4. *Practical contribution:* taking care that what is unnecessary is done as little as possible.

5. *Suggested name for practical application of the view:* flow management.

This research directly used 1. Conceptualisation and 2. Main principle. The three remaining steps (3-5) are of high relevance when the aim is to remove waste thus highly relevant when the findings of this research are to be used.

The WS method is in this research used to depict the flow by using multiple categories directly reflecting all Koskela (2000) conceptual categories except from "inspection". As an example, DW depicts the value-adding work and hereby the time directly spent on the transformation.

The main principle of eliminating waste or NVAW, also fits with the WS method. The WS method has the DW category describing the transformation or value-adding work, and several other categories designed to describe how the NVAW time is used. This enables a deep analysis of the NVAW time, and hereby waste, in the production system and as outlined in Ohno (1988); Rother and Shook (2003), understanding and seeing waste is a key to eliminating it. Previous work on WS data also perceived all categories but DW as waste (Skovbogaard 2017) since they are sought minimized, but the link between waste and the flow view was not created. Finally, eliminating waste is a key to increase craftsmen time used on DW and because DW is positively correlated to CLP (Neve, Wandahl, Lindhard, et al. 2020), also a key to increasing CLP in renovation projects.

Vast quantities of research have previously used the WS method in construction. None of these have though applied it to analyse and identify production system behaviours in a construction production system from the perspective of flow. Thus, this research aims, not only to close a gap within construction renovation, but also showcase a new approach for the use and analysis of the WS method and its data by answering two research questions.

1. What is the baseline of Direct Work in renovation projects?
2. Which Direct Work and Non-Value-Adding Work time behaviours exist in a renovation production system?

Answering the research questions will provide an understanding of the current state of the renovation production system and provide insights to how a more productive future state can be reached.

4. Method

Yin (2009) outlines four types of research design for case studies: 1) single case and single unit of analysis, 2) single case and multiple units of analysis, 3) multiple cases and single unit of analyses, and 4) multiple cases with multiple units of analysis. This research chose the third research design proposed with multiple cases and a single unit of analysis. The research design was chosen because it enabled deep research of the unit of interest namely time flow in three cases. Using three cases further enabled the researcher to understand how time flow behaved across cases and to understand if behaviours were similar or different. Using three cases also increases the replicability of the research. The data collection was done with the WS method. The method section will firstly introduce the three cases. Secondly, the WS data collection will be outlined. Finally, the analysis will be described.

4.1 Cases

Three cases of renovation projects were chosen. The cases are summarised in Table 1. The cases were chosen based on two criteria: 1) they had to be renovation projects, and 2) they needed to be alike to compare production system behaviours. The chosen cases' original building structure and floor plan was very similar, and they were planned to go through comparable deep renovations including the building envelope, interior and installations. All cases were social housing renovation projects consisting of apartments (number for each is outlined in Table 1). All cases were located in alike cities in the western part of Denmark. Five trades were selected in each case for the planned work sampling study. The number of trades for each case was chosen to represent the majority of work in progress, so the production system behaviour of each case could be analysed and compared. Furthermore, the trades had to include traditional renovation work such as carpentry, painting, masonry, so forth, which would occur on any renovation project. The trades are outlined in table 1. All trades were followed within the same period, which was crucial for understanding how the different trades affected each other. Furthermore, all data were collected at times during the projects that were not close to neither project start-up nor completion, thus representing normal production conditions.

Table 1. Data collection from three cases

	Case 1	Case 2	Case 3
Contract type	General contractor	Turnkey contractor	General contractor
Contract value [USD millions]	31	53	55
Contract [Years]	5	4	4
Apartments [No.]	291	297	601
Area [m2]	22.800	23.700	46.500
Stories	Basement to 2	Basement to 2	Basemen to 3
Originally built	1950s	1960s	1950s
Focus of WS study	5 trades:	5 trades:	5 trades:
	Barge and Façade	Plumbing	Plumbing
	Façade	Decking	Plastering
	Demolition	Painting	Painting
	Masonry	Kitchen	Tiling
	Flooring	Flooring	Concrete

4.2 Work sampling

Work sampling was chosen because it is a suitable method to collect data on how time is being used by crafts on a construction project. The WS method is quantitative and based on direct observations of the work of interest. To quantify the observations, these are organized in predefined categories. The categories were defined to adequately describe the work observed and fit the purpose of the WS study.

This research applies seven categories to describe the observed work, and the categories are outlined in Table 2 below. The category of DW is the only category which reflects value-adding work, and hereby the transformation, for the work observed. The remaining categories describes the NVAW.

Table 2. Definition and description of observation categories. Adopted from Wandahl and Skovbogaard (2017)

Category	Description
Direct Work	Activities that physically add value to the product, processing of materials or assembling of an interior element (e.g., module in kitchen).
Talking	The time used to discuss drawings or work at hand, conversations with persons outside the crew such as tenants or managers. There is no distinction between professional and private talk.
Preparation	Non-value-adding handling of materials and elements, adjustment and cleaning of machines and tools, looking for tools or materials, and measuring and marking.
Transport	Driving in a truck to move materials, carrying materials or tools from one place to another.
Walking	Walking without carrying any tools or materials from one place to another.
Gone	Time absent from the construction site, such as visits to the toilet and smoking.
Waiting	Time spent waiting for co-workers, information, and materials.

At least 510 datapoints (observations) were collected for each sample. The number of observations follows Thompson (1987) and Thompson (1992) previous recommendations on number of datapoints necessary for obtaining 95% confidence in work sampling studies. Furthermore, Gouett et al. (2011) and Hwang et al. (2018) followed the same recommendations when collecting WS data. The data samples' validity was furthermore checked by using stabilization curves. A stabilization curve is a data plot with the x-axis being data points and y-axis being the relative percentage. The more data you collect the more stable should each category become.

The data was collected according to the following protocol. The WS data was collected by having one observer follow each of the five trades on each case. Five research assistants were employed in each case to help gather the WS data, and they were instructed to use pen and paper for data collection. This meant that every time they did a direct observation, a mark was put on a piece of paper in the category they believed that the work represented. All research assistants received thorough instruction both off and onsite before start of the work sampling. The observers followed the work from start until finish no matter the time to depict time use in both ends of the working day for all trades. The only time that the observers did not register observations was in the agreed breaks the crafts took in regular intervals. If crafts spent more time on breaks than agreed, this would be categorised as 'Gone' time. All observers were supervised during the data collection. This meant that that the supervisor took multiple site tours during a day to observe how the assistants categorised work and hereby continuously secure validity and continuity in the collected data.

The role of the observer has previously been discussed, showing two different views. Jenkins and Orth (2004) argue that the observer's knowledge about the construction process is crucial whereas Josephson and Björkman (2013) argue that young unexperienced observers are less biased towards accepting time spent on preparation as direct work. This research agrees with both meaning that both highly experienced professionals and inexperienced students can collect the data. This research must though emphasize that when using unexperienced observers, instruction and supervision during data collection is important for obtaining valid data.

4.3 Data analysis

Data presentation and trends

The data is firstly presented with relative frequency and number of observations per category for each case and its observed trades. This generates an overview of the collected data which is crucial for the validity and trustworthiness of the research. The relative frequency is calculated by dividing the given trade or case observations in a category by the trade or case' total number of observations.

Following this, day curves are generated for each case to investigate system behaviours. These curves are generated by normalising each trade so it can be compiled into one representing the case. Normalisation was necessary because the trades did not have the same working time, durations, and breaks during the day. Normalisation was done by dividing all days into three parts separated by the break 1 and break 2. Due to normalisation of the day curves time stamps could not be applied. Instead, the x-axis clearly states when the workday starts, ends, and contains break 1 and 2.

Statistical analysis and system behaviour

Statistical analysis was conducted to further understand the production system of the three cases. The statistical analysis was conducted on the case level. Linear regression analysis was used for this. The analysis was done by analysing how each of the six non-value-adding WS categories: talking, preparation, transport, walking, gone, and waiting influenced the value-adding category of DW. DW is, in the analysis, set to be the

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dependent variable, with the other six acting as independent variables. This is done because the category of primary interest is DW since this reflects how much time the trade or case is using on value-adding work.

5. Results

5.1 Research question 1

The first research question is answered by compiling all the data obtained from the WS studies conducted on the three cases. In total 15 trades were included.

Research question 1: What is the baseline of Direct Work in renovation projects?

The compiled WS data is presented in Table 3, with both the relative frequency (%) and the number of observations (N) for each category. As the table shows, the baseline of DW is 29.5% of the total work time hereby answering research question 1.

Table 3. WS baseline for all cases. WS data compiled, N=47493

		Value-adding	Non-Value-Adding (Waste)					
Categories		Direct Work	Talking	Preparation	Transport	Walking	Gone	Waiting
All cases	(%)	29.5%	18.2%	19.1%	7.4%	6.4%	13.5%	5.9%
[Average]	(N)	14000	8664	9053	3530	3049	6401	2796

5.2 Research question 2

To answer research question 2, a detailed presentation of the WS data is necessary to enable the readers to understand the origin of figures and statistics used in the analysis.

Research question2: Which Direct Work and Non-Value-Adding Work time behaviours exist in a renovation production system?

Firstly, the three cases are presented in detail in Tables 4 to 6. The tables' first row outlines the seven WS categories, and the first column states the data sources, followed by the second column stating whether it is the relative frequency (%) or number of observations (N) which is shown. The three tables start by outlining the cases' average, followed by the in-depth data presentation of the five trades from each case from which the case average is calculated.

The first system behaviour: Case Variance.

Case variance is due to the variance in the trades' DW levels in each case. This is outlined below where the three cases are listed with each case's DW average followed by the DW level from the lowest- and highest-performing trades. This shows that a large variance exists between the trades in each case. From Tables 4 to 6:

- Case 1: avg. 26% DW, low. 18.6% DW and high 40.5% DW
- Case 2: avg. 33% DW, low 17.8% DW and high 52.6% DW
- Case 3: avg. 36% DW, low 20.7% DW and high 51.8% DW

The finding is important when measuring DW with the aim of increasing the DW percentage because, in this case, one must measure both on trade and project level to understand the average DW and where the potential lies.

This is equivalent to measure performance in manufacturing, where knowledge is needed on both the overall production line performance and the individual machines to know where the biggest potentials are located. In construction, each trade would be the equivalent of a machine in an assembly line.

Table 4. Case 1 work sampling data

Categories		Direct work	Talking	Preparation	Transport	Walking	Gone	Waiting
Barge & Facade	(%)	26.9%	17.5%	15.9%	7.4%	6.3%	20.3%	5.7%
	(N)	1589	1034	941	435	369	1198	338
Facade	(%)	20.2%	27.1%	18.7%	8.1%	4.4%	17.0%	4.6%
	(N)	2113	2839	1963	848	457	1782	477
Demolition	(%)	18.6%	26.2%	9.6%	5.7%	9.9%	12.7%	17.3%
	(N)	864	1215	446	266	458	589	803
Masonry	(%)	34.3%	10.5%	17.1%	6.4%	8.5%	18.8%	4.5%
	(N)	2081	637	1039	387	513	1139	274
Flooring	(%)	40.5%	19.1%	10.6%	13.5%	3.5%	8.7%	4.0%
	(N)	1130	534	295	378	99	243	111
Case 1 [Average]	(%)	26%	21%	16%	8%	6%	17%	7%
	(N)	7777	6259	4684	2314	1896	4951	2003

Table 5. Case 2 work sampling data

Categories		Direct work	Talking	Preparation	Transport	Walking	Gone	Waiting
Plumbing	(%)	52.6%	9.9%	10.1%	2.7%	4.6%	18.9%	1.2%
	(N)	389	73	75	20	34	140	9
Decking	(%)	17.8%	11.9%	35.5%	8.6%	8.5%	15.8%	1.8%
	(N)	151	101	301	73	72	134	15
Painting	(%)	39.6%	21.8%	14.8%	6.2%	7.4%	9.7%	0.6%
	(N)	322	177	120	50	60	79	5
Kitchen	(%)	34.0%	12.1%	27.8%	9.3%	8.8%	6.5%	1.5%
	(N)	182	65	149	50	47	35	8
Flooring	(%)	25.3%	16.5%	27.2%	18.0%	6.0%	3.0%	3.9%
	(N)	251	164	270	178	59	30	39
Case 2 [Average]	(%)	33.0%	14.8%	23.3%	9.4%	6.9%	10.6%	1.9%
	(N)	1295	580	915	371	272	418	76

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Table 6. Case 3 work sampling data

Categories		Direct work	Talking	Preparation	Transport	Walking	Gone	Waiting
Plumbing	(%)	35.7%	6.2%	29.6%	13.1%	7.2%	8.0%	0.2%
	(N)	478	83	396	176	97	107	3
Plastering	(%)	20.7%	12.7%	34.0%	9.1%	10.1%	12.7%	0.7%
	(N)	285	175	468	125	139	175	9
Painting	(%)	51.8%	13.1%	12.2%	5.2%	7.8%	9.7%	0.2%
	(N)	1719	433	406	172	260	320	6
Tiling	(%)	43.8%	10.1%	28.2%	5.4%	3.5%	8.7%	0.4%
	(N)	1560	358	1005	192	124	309	14
Concrete	(%)	21.7%	19.0%	28.8%	4.4%	6.4%	3.0%	16.8%
	(N)	886	776	1179	180	261	121	685
Case 3 [Average]	(%)	36.0%	13.3%	25.2%	6.2%	6.4%	7.5%	5.2%
	(N)	4928	1825	3454	845	881	1032	717

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The second system behaviour: Trade Performance.

Trade performance is analysed by perceiving the three cases as one. The behaviours are deducted from Figure 1 that presents the 15 trades from all three cases, arranged from highest DW (left side) to lowest DW (right side).

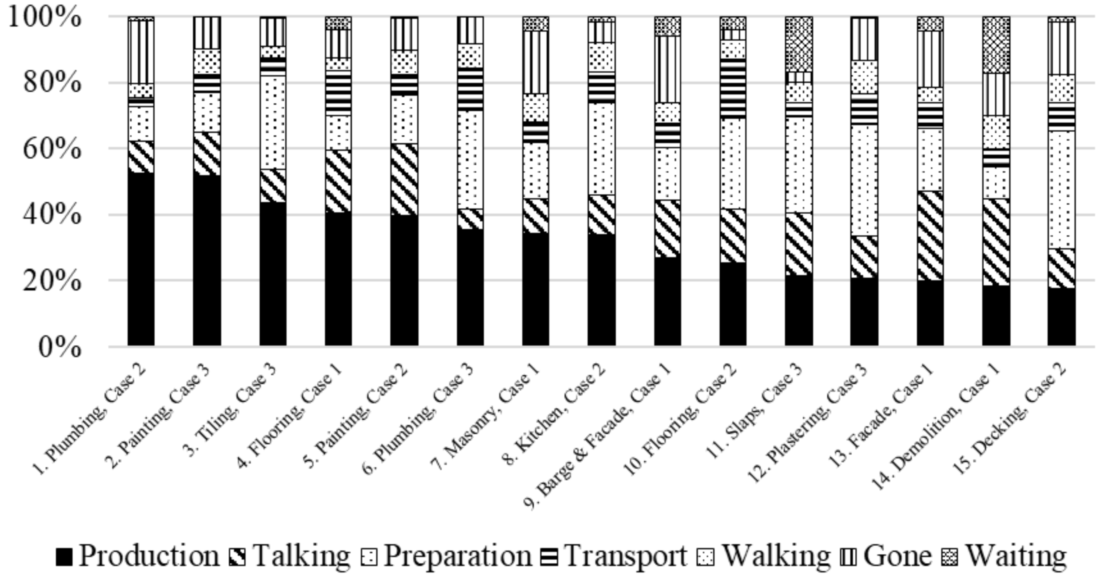


Figure 1. Trades arranged by DW level.

In the following, the behaviours deducted from Figure 1 are described:

1. There is no connection between the type of work the trades do and their DW levels. This is seen when looking at the three trades with the highest DW values: 1. Plumbing (52.6%), 2. Painting (51.8%), and 3. Tiling (43.8%) and the three trades with the lowest DW values: 13. Facade (20.2%), 14. Demolition (18.6%), and 15. Decking (17.8%). Both the three highest- and the three lowest-performing trades are different regarding work type. Furthermore, the three highest- and three lowest-performing trades are also not related. This shows that the type of work the trades perform is not a deciding factor for the achieved DW levels.
2. No trend exists regarding which of the categories one should focus on when trying to increase DW. When looking at Figure 1 and following the development in DW level from lowest to highest, one can see that the remaining six NVAW categories have no trend in how they relate to the level of DW. This trend shows us that no generic targets can be set for the NVAW categories.

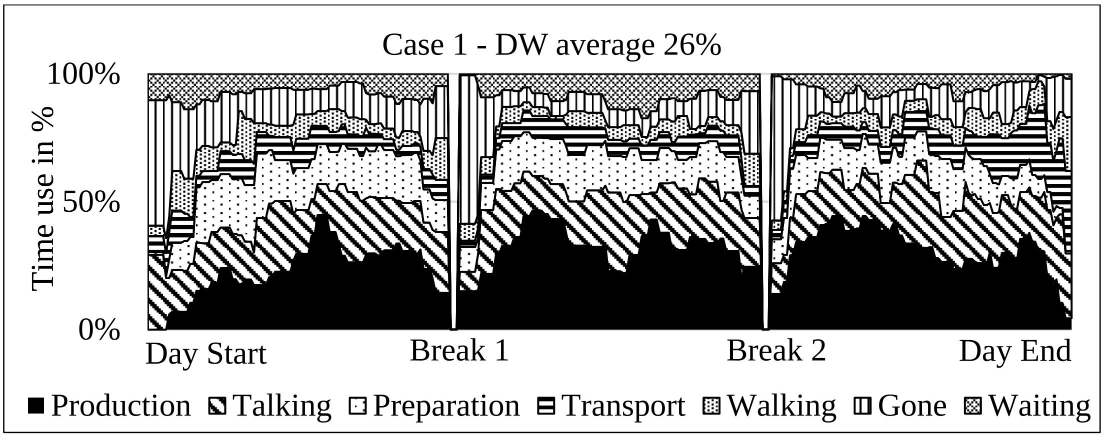
The above will be useful when the discussion addresses the implications these results have for increasing time spent on DW.

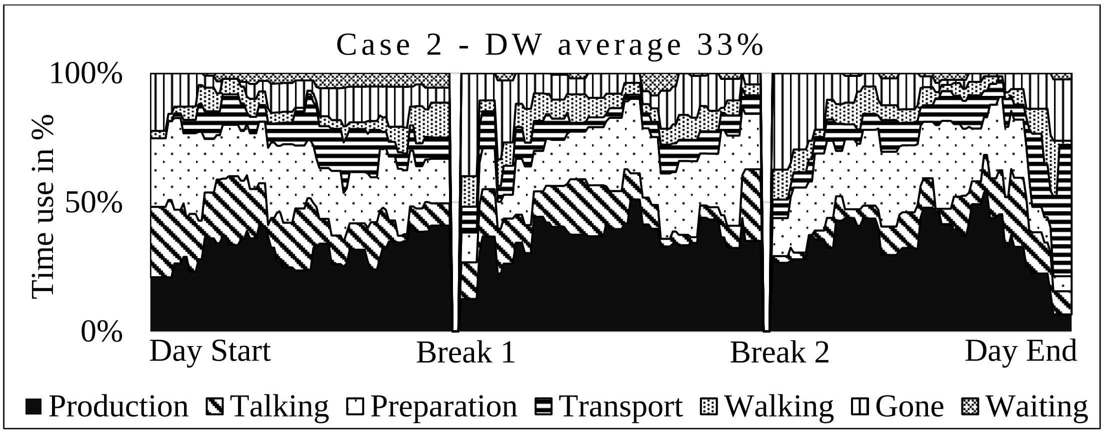
The third system behaviour: Starts and Stops.

Starts and Stops is identified through the normalised day curves for the three cases shown in Figure 2. The day curves are purposely arranged with lowest to highest performance to highlight the production system behaviour of interest. The production system behaviour of interest is the time it takes for work to start-up in the morning and after the two breaks, and, how long it takes to slow it down before the two breaks and at the end of the day. The day curves reveal a trend. The lower the average DW, the longer it takes both to get the work started and to slow it down.

The fourth system behaviour: High Performance and High Stabilisation.

High performance and high stabilization are also revealed by the day curves. It shows that the higher the level of average DW, the more stabilised are the DW levels over the day.





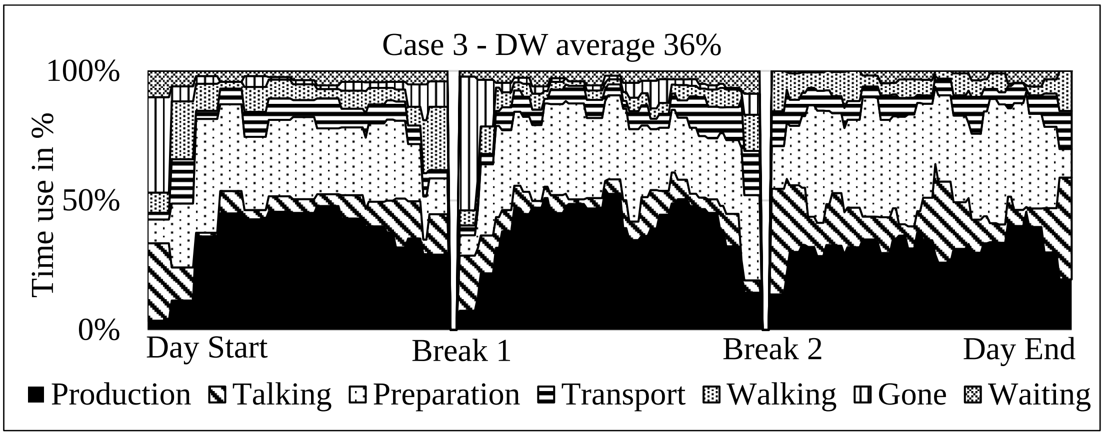


Figure 2. Normalised day curves for cases 1, 2, and 3

The fifth system behaviour: Influence of Categories.

Influence of categories is identified using linear regression analysis. The linear regression analysis is used to describe how each of the NVAW categories – talking, preparation, transport, walking, gone, and waiting – influence DW. The results of the analysis are presented in Table 7. The table presents three key information's from the linear regression analysis with: 1) the predictor coefficient (A) from the standard linear function y=Ax+B, 2) the regression coefficient (R), and 3) the statistical significance level (*p*).

Table 7. Relationship between Direct Work and the six non-value-adding categories

Relationships	Case 1			Case 2			Case 3		
	A	R	*p*	A	R	*p*	A	R	*p*
Direct Work Talking (1)	-0.558	.459	.000	-0.411	.268	.021	-0.496	.393	.000
Direct Work Preparation (2)	-0.655	.333	.000	-0.563	.525	.000	-0.532	.443	.000
Direct Work Transport (3)	-0.273	.122	.186	-0.338	.216	.074	-0.703	.273	.008
Direct Work Walking (4)	-0.883	.286	.002	-0.658	.187	.022	-1.359	.464	.000
Direct Work Gone (5)	-0.380	.326	.001	-0.199	.155	.009	-0.558	.361	.001
Direct Work Waiting (6)	-0.223	.134	.161	-0.159	.040	.849	-0.177	.138	.474

The six relationships outlined in Table 7 are then plotted in Figure 3 to provide a visual representation of the production system behaviour regarding how the six NVAW categories influence (A) on DW. In Figure 3, the y-axis represents the percentage level of DW, and the x-axis represents the percentage level of the NVAW categories: talking, preparation, transport, walking, gone, and waiting. The number between 1-6 given to each line on each case's graph tells what relationship is being depicted with reference to the number in the first column in Table 7 above.

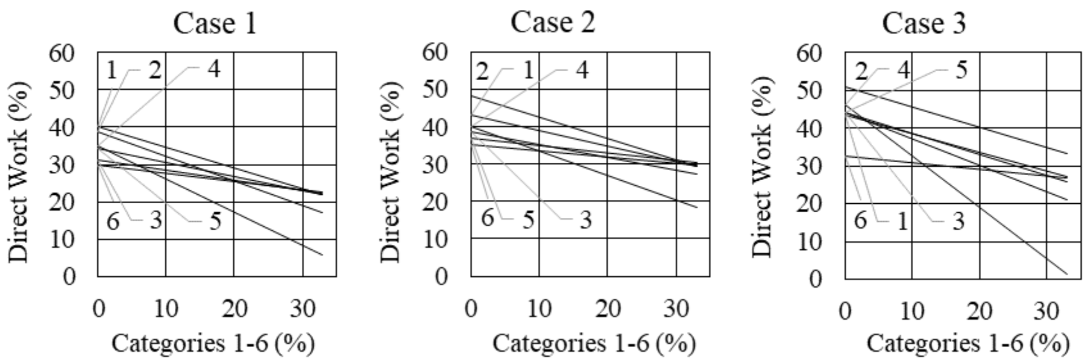


Figure 3. Plotted relationship between direct work and six non-value-adding categories

The result presented in Table 7 and Figure 3 reveal that the fifth system behaviour can be described as a group of how the NVAW categories influence each other:

1. The Predictor coefficient (A) described in Table 7 and depicted in Figure 3 shows that waiting is the NVAW with the smallest influence on DW in all three cases. This is clear because A has the smallest value in all cases (Table 7) and most horizontal line (Figure 3). Looking at Table 7, Waiting also reveals itself as having both low statistical confidence (*p*) and low predictive capabilities (R) in all cases, making it the category with the smallest interest when aiming at increasing DW.
2. Walking stands out at the other end of the spectrum as being of high interest regarding increasing DW time. Walking has the highest influence on DW in all cases looking at the predictor coefficient (A), which is depicted in Figure 3 with the number (4) for all three cases. Furthermore, the statistical significance level is above the 95% level and R levels in the low but acceptable range. This means that Walking should be the primary category of interest to reduce when aiming at higher DW levels.
3. The statistical analysis presented in Table 7 and plotted on Figure 3 shows that the three cases systems behaves similarly when considering how the six NVAW categories influence DW. Looking at Figure 3 one can see that walking in all cases have the steepest slope with all the remaining being grouped closely with similar slopes.

6. Discussion

The results provide a theoretical contribution to the long-standing discussion on waste in construction which has been summarised in Tzortzopoulos et al. (2020). This research provides insights to how NVAW and hereby waste behaves and influence DW. It further provides a novel approach to waste analysis in the TFV production theory's (Koskela 2000) flow view, were the production resource is time (Bølviken et al. 2014). This research's analysis aligns with the conceptual description and main principle in the original description of the TFV theory's flow view (Koskela 2000) but do not fully encapsulate the described time loss wastes in Bølviken et al. (2014). Furthermore, the research provides a practical overview of how DW and NVAW flows through (behaves in) the production system of renovation. This can be directly used by any industry consultant. The baseline and behaviours are in the following discussed, compared to previous research and potentials for further research is presented. The matter of how to increase DW through waste reduction is outlined in the end of the discussion.

6.1 DW baseline

The identified 29,5% DW baseline firstly enables others to compare results and behaviours. More importantly, it shows the current state in which the following five discussed behaviours has been deducted. As the following will show, a DW average above 50% for a case seem possible and further research is needed to understand systems behaviours with significantly higher DW levels.

6.2 Case Variance

The first production system behaviour, *Case Variance*, shows large variations in DW levels between the trades in cases 1, 2, and 3. This finding aligns with previous findings outlined in the introduction (Björkman et al. 2010; Kalsaas 2010; Josephson and Björkman 2013; Kumar et al. 2014; Shahtaheri et al. 2015; Sheikh 2016; Sheikh et al. 2017).

Knowing that DW varies between trades in each case enables planning of a better data collection and analysis. The reason is, that we now know, that when measuring DW, one needs both the case level and detailed DW levels of the trades, to know how your construction production system is behaving and where to look for potentials. If the measurement of DW is done only on the case level, one would be looking blindly for improvement potentials, whereas focusing only on one trade's DW levels would be measuring only point speed, not the system.

6.3 Trade Performance

The second system behaviour, *Trade Performance*, reveals a remarkable lack of trends regarding the relationship between work type and measured DW level. This lack of trend is also found in previous work showing that even the same trade can have different DW levels within the same project and across multiple projects (Logcher and Collins 1978; Thomas 1981; Olomolaiye et al. 1987; Handa and Abdalla 1989; Salim and Bernold 1994; Strandberg and Josephson 2005).

That the work type is not the deciding factor for DW levels, can be utilised when setting DW targets. One can now set a DW target for the whole construction project and from here on analyse the individual trades' actual level of performance.

Looking into the results further, these show that the two best-performing trades are the plumber from case 2 with DW at 52.6% and the painter from case 3 with DW at 51.8%. Knowing that two different types of trades can reach above 50% in DW within their respective production systems leads the authors to believe that DW targets for renovation projects should be at least 50%.

The second part of the system behaviour, *Trade Performance*, outlined that no relationship exists between DW levels and the ratio between the 6 NVAW categories. This do, to some degree, increase the challenge of decreasing NVAW categories because assigning NVAW targets cannot be done. Recognising previous research's (Shahtaheri et al. 2015) attempt to set targets for all categories emphasizes the need for further research since different approaches provides different conclusions.

6.4 Starts and Stops

The third system behaviour, *Starts and Stops*, shows that all cases waste time on slow starts and stops around morning start-ups, breaks, and closing time. It also reveals that cases with higher average DW levels waste lesser amounts of time. Similar behaviours have previously been shown (Björkman et al. 2010; CII 2010; Gouett 2010; Gouett et al. 2011; Shahtaheri 2012; Hajikazemi et al. 2017; Skovbogaard 2017; Hwang et al. 2018). This show that this behaviour is not unique to renovation systems but visible across different project types.

The knowledge can further be utilised when project managers want to increase a project's DW levels because, with this knowledge, they can strategically allocate additional resources at the time were the day curves reveal performance challenges. Especially starting-up the work more efficiently in the morning to gain a higher average DW level matches well with Hwang et al. (2018) who found that this time of the day contained big potentials.

6.5 High Performance and High Stabilisation

The fourth system behaviour, *High Performance and High Stabilisation*, shows that higher levels of average DW equals more stable DW levels. This finding aligns with the previous work on construction production system improvement, which shows that stabilising workflows is a key ingredient of higher performance (Tommelein et al. 1999; Gonzalez et al. 2008; Zegarra and Alarcón 2013; Lindhard 2014; Zegarra and Alarcón 2017; Abou-Ibrahim et al. 2019; Lindhard et al. 2019). Stabilisation of work as an integrated part of improving performance in construction is also known from the lean construction community that have advocated for this for decades.

6.6 Influence of Categories

The fifth system behaviour, *Influence of Categories*, reveals that the WS category of walking influences DW more than the remaining five categories of talking, preparation, transport, gone, and waiting. This can be utilised when the methods of WS are to be used by a renovation project for increasing time spent on DW. The reason is that instead of having to focus on all six non-value-adding categories, one can focus on reducing the amount of time craftsmen spend on walking. Focusing on walking has two advantages. Firstly, it's easily recognisable which is a precondition for reducing any waste according to Ohno (1988) and Rother and Shook (2003). Secondly, one can find the root cause of any walking by using the approach of 5 whys' in a quick conversation with the onsite craftsmen. Understanding the chain of causality between WS categories and which of these contains the biggest potentials for being reduced is a topic for future research.

6.7 How to increase DW in renovation projects

This research provides an additional step towards better understanding NVAW time (waste) in construction by revealing five behaviours for DW and NVAW time. The five behaviours is a step towards fully learning to see and understand waste in renovation projects, which according to Ohno (1988); Rother and Shook (2003), is essential if it is to be removed.

That a link exist between variability and waste (Tommelein et al. 1999) is though recognised by the authors thus reducing waste means both understanding waste and variability since they are interconnected in a production system. The authors further agree with Tzortzopoulos et al. (2020) on the fact that Lean Construction is an instrumental tool in reducing waste and variability in construction renovation projects.

This is furthermore in line with Koskela (2000) last three parts of his integrated TFV view on production: A) *Methods and practices:* continuous flow, pull, production control, continuous improvement, B) *Practical contribution:* taking care that what is unnecessary is done as little as possible, and, C) *Suggested name for practical application of the view:* flow management.

A, outlines that lean methods and practices as continuous flow, pull production control and continuous improvement should be used to execute what he names flow management (C). These have the overall practical contribution (B) of: *"Taking care that what is unnecessary is done as little as possible"*.

7. Conclusion

Since construction labour productivity is stagnating or declining in most countries, more knowledge on the labour-intensive renovation production system is needed to enable a much-needed change. This research collected data from 15 trades equally spread over three renovation projects using the work sampling method. The data analysis focused on direct work ((DW), value-adding work) time and non-value-adding work (NVAW, also known as waste) time in the production system. The analysis firstly, revealed that the three renovation production systems had a DW baseline of 29.5%. Secondly, five system behaviours were identified showing how DW and NVAW behaves in a renovation production system. The increased understanding of how DW and NVAW behaves is an important step towards changing status que with low DW levels. These findings have implications for both academics and practitioners. Academics were shown a new approach to data analysis giving a novel understanding of DW and NVAW in renovation production systems. Furthermore, the discussion presented concrete insights and advise to, among others, data collection, analyses and target setting directly applicable by any process consultant in industry.

7.1 Limitations

The research has the following limitations. Firstly, this research used 3 similar cases from renovation construction projects. This is a limitation of the research because the findings have not been replicated in other types of construction projects. Secondly, the research used research assistants when collecting the work sampling data. This is a limitation because the observations and hereby data can be biases and interpreted differently. The limitation was though mitigated using a thorough protocol.

7.2 Future research

These research findings builds the foundation for the following branches of future research.

1. The work time behaviours were explored in three cases with average DW levels at 26%, 33% and 36%. Exploring the same behaviours in case with average DW levels at e.g. 50% would provide novel insights to whether work time behaviours are consistent across all levels of DW thus an important topic for future research.
2. The work time behaviours should be researched in other project types to test their replicability.
3. Previous research have found that targets can be set for NVAW categories whereas this research finds the opposite thus future research should investigate this topic further.
4. The chain of causality between the NVAW categories is a topic for future research. The topic is important because it would enable deeper understanding of the root causes of wasted work time
5. Future research should explore if the use of lean tools can affect DW and NVAW time so future construction project can be executed more efficiently.

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9. Disclosure statement

No potential conflict of interest was reported by the authors.

10. Data availability statement

Data generated or analysed during the study are available from the corresponding author by reasonable request.

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