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A NEW MODEL FOR CONSTRUCTION MATERIAL LOGISTICS: FROM LOCAL OPTIMIZATION OF LOGISTICS TOWARDS GLOBAL OPTIMIZATION OF ON-SITE PRODUCTION SYSTEM

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ABSTRACT

Research on construction on-site material logistics has mainly concentrated on how to best deliver materials on site or how to store the materials in constrained space. Less research has been done on the impact of logistics on labor productivity. The purpose of this research was to review empirical results related to logistics and labor productivity reported in literature as well as previous research on construction material logistics to come up with requirements of a new lean model for material logistics. Current research on construction logistics was found to focus on part of the problem and to offer partial solutions rather than globally optimize the production system. Indirect costs of logistics causing interference to other tasks or waste due to material transportation have not been extensively discussed but several empirical results can be potentially explained by logistics even though the research was not about logistics. The paper proposes a new model for construction material logistics and hypotheses to be evaluated in future empirical research or simulation studies. The paper is valuable for academics with research interests in construction logistics or productivity areas and for practitioners seeking productivity improvements.

KEYWORDS

Lean construction, logistics, inventory control, productivity.

INTRODUCTION

Logistics accounts for a large part of the total cost of a construction project. In contrast with other industries most of the money is spent on site, handling material as opposed to transportation outside the project (Elfving et al. 2010). This makes on-site logistics a very important improvement area for contractors. Most attention has been given to congested projects with limited site storage possibilities. Interestingly, despite the challenge of space, the direct observation of authors on several projects with limited storage space, echoed with Mossman's (2007) observations, indicate that production planning is better done on tight sites which results in an overall

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improvement in the process. We do not know if this is because logistics is critical for the performance of on-site production system, better planning of logistics requires more from other planning aspects or better teams are selected for difficult projects.

Motivated by these observations we set out to review what research results have been reported for various aspects of logistics. Our goal was to identify all the relevant aspects of on-site production system from logistics points of view and review empirical evidence to identify what we know and which aspects have been ignored by research. Our hypothesis was that logistics research has been based on single case studies and each study focuses only on small part of the problem. In particular, we thought that most of the logistics research focuses on the cost of logistics or delivery reliability and ignore aspects tied to labor productivity, for example due to interference or carrying materials by skilled labor.

METHODS

A literature review was performed related to construction logistics and empirical research on productivity. A search was performed in Google Scholar with keywords "Construction logistics" and "Construction project productivity empirical research" and the first 15 pages of hits were considered for relevance. Additionally IGLC database was searched with keywords "logistics" and "productivity". The abstracts of all found papers were reviewed to evaluate their relevance and the full paper was reviewed if the abstract was relevant. A logistics paper was deemed relevant if it was clearly related to construction logistics. A productivity paper was deemed relevant if it included empirical data, which was somehow collected on field. In total, 26 logistics related papers and 22 empirical productivity related papers were reviewed in full.

The logistics literature was categorized based on problem statement (i.e. how the problem of construction logistics was formulated) and the proposed solutions (if any). The categories were used to formulate an overall model of logistics based on constructive research principles. Empirical results related to productivity were then analysed related to the logistics model to identify gaps in knowledge. Finally, research questions were proposed to address these gaps.

LITERATURE REVIEW

CONSTRUCTION LOGISTICS PROBLEM STATEMENT

Logistics was approached from several different viewpoints. Table 1 shows the list of papers and the viewpoints they chose for logistics. Most papers considered three or four viewpoints simultaneously (11 papers). There were very few attempts to discuss logistics broadly. However, Mossman's (2007) paper is an important exception and was an attempt to highlight several important aspects of logistics.

Table 1: Logistics viewpoint of different papers

Authors	Logistics viewpoint									
	Costs	Inventory	On-time delivery	Storage location	Transport equipment/distance	Inter-ference	Queue of transport vehicles	Supplier's viewpoint	Impact of design	Satisfaction
Arbulu & Ballard (2004)		x	x							
Arbulu et al (2005)	x	x		x						
Bertelsen & Nieslen (1997)	x		x							
Bortolini et al. (2015)		x		x						
Caron, Marchet & Perego (1998)	x		x							
Cheng & Kumar (2015)			x	x						
Elfving et al. (2010)				x	x					
Hamzeh et al. (2007)			x							
Ibrahim & Hamzeh (2015)					x				x	
Jang, Russell & Yi (2003)										x
Kalsaas et al. (2011)	x			x	x					
Lange & Schilling (2015)			x	x	x					
Mossman (2007)	x	x	x	x		x			x	
Ng, Shi & Fang (2009)		x	x		x		x			
Nguyen et al (2008)								x		
Pinho, Telhada & Carvalho (2008)	x	x								
Said & El-Rayes (2013)	x			x	x					
Said & El-Rayes (2014)	x			x		x				
Salagnac & Yacine (1999)	x		x					x		
Silva & Cardoso (1999)	x	x	x							
Skjelbred, Fossheim & Drevland (2015)			x			x	x		x	
Sobotka & Czamigowska (2005)	x	x								
Vidalakis, Tookey & Sommerville (2011a)	x	x						x		
Vidalikis, Tookey & Somerville (2011b)								x		
Voigtmann & Bargstädt (2010)				x	x	x				
Wegelius-Lehtonen, T (2001)	x									

Decreasing the cost of logistics from the point of view of contractors was the most common viewpoint. Logistics cause extra costs which are not related to transportation if materials are not on site when required, materials are incorrect or if there are large amounts of materials on site which tie up capital (Arbulu et al. 2005). Costs can also increase due to wasted labor because workers are looking for materials and management time is expended to manage inventories and materials can be damaged (Arbulu & Ballard 2004). Wegelius-Lehtonen (2001) focused on performance measurement of logistics, calling for process metrics. For example, purchase price is not a good metric because buying in bulk may lead to lower unit price but ignores the cost of logistics.

Decreasing inventories was highlighted especially in congested projects (Mossman 2007; Said & El-Rayes 2013; Said & El-Rayes 2014). Importantly, Mossman (2007) noted that projects with congested sites require detailed planning of logistics and it seems that these projects go better in other respects as well. Obviously inventories and material buffers are against the lean philosophy and this angle has been adopted in several papers (Arbulu & Ballard 2004; Arbulu et al. 2005). However, sizing inventory is a matter of balancing customer service level with total logistics cost (Silva & Cardoso 1999).

Inventory is tied to on-time delivery of materials. Caron, Marchet and Perego (1998) investigated the optimal material buffer to achieve a desired level of protection against material shortages. On-time deliveries are at risk when deliveries are done by each subcontractor trade (Lange & Schilling 2015) and by the truckload (Bertelsen & Nielsen 1997). In this respect, the suppliers have a very different optimization problem. For example, Builders' Merchants are supplying materials for several construction sites and hold contingency inventories for a large number of contractors. (Vidalikis, Tookey & Sommerville 2011a). They lose money if they do not optimize the use of their transportation capacity. It does not make sense for them to move to Just-in-Time delivery because they need full trucks and minimized distances to stay profitable (Vidalikis, Tookey & Sommerville 2011b). Several case studies of Make-to-Order producers highlight that the suppliers minimize their cost by producing one type of element in long runs and shipping the materials by type (or size) (Salagnac & Yacine 1999; Nguyen et al 2008). These results highlight the conflicting goals of various actors in supply chain.

Logistics can also be viewed from the waste point of view. Waste can result from incorrect offloading resources (Elfving et al. 2010), moving material several times (Elfving et al. 2010; Voigtmann & Bargstädt 2010) and interference of storage areas with work (Voigtmann & Bargstädt 2010; Said & El-Rayes 2014). The distance of storage area to work area is an important source of waste due to horizontal transportation often done by skilled labor (e.g. Elfving et al. 2010; Ng, Shi & Fang 2009; Said & El-Rayes 2014).

LOGISTICS SOLUTIONS IN LITERATURE

To tackle the various logistics problems in construction, a wide variety of solutions have been proposed in literature. Table 2 presents an attempt to categorize the solutions. Centralized logistics centers, typically including kitting, were the most commonly proposed solution. Authors pointed to the need of improved scheduling and to Just-in-time deliveries. Digital tools including simulation or optimization, web-based system for logistics or solutions based on Building Information Modeling were often proposed. Other solutions included using a separate logistics company, increased standardization or pre-assembly and methods to size the material inventory or safety stock optimally.

Logistics centers in construction can support multiple logistics functions, such as storage, transport, distribution and kitting (Hamzeh et al. 2007). They make possible just-in-time deliveries to construction sites and buffer against variability in activity start dates and durations (e.g. Arbulu and Ballard 2004). A great opportunity given by logistics centers is the ability to prepare location-specific delivery packages (kits) which can be delivered to the point of installation to increase productivity (Elfving et al. 2010).

Several authors have proposed improved scheduling or production control as a counter-measure. For example, several authors from the lean community (e.g. Arbulu & Ballard 2004; Arbulu et al. 2005; Mossman 2007) call for the use of Last Planner System to make sure that all the prerequisites meet at the right time. Other approaches involving scheduling include optimizing start dates of tasks within their total float so that space is allocated to interior storage areas which are in turn optimized based on space constraints and proximity to work (Said & El-Rayes 2014).

Table 2: Logistics solutions categorized based on literature

Authors	Logistics solution									
	Centralized logistics / logistics centers / kitting	Kanban / Just-in-Time	Improved scheduling / LPS	Buffers / safety stock	BIM-based solutions	Simulation-based solutions / optimization	Web-based logistics software	Standardization / pre-assembly	Logistics company	Other
Arbulu & Ballard (2004)	x	x	x				x	x		
Arbulu et al (2005)		x	x				x			
Bertelsen & Nieslen (1997)	x	x								
Bortolini et al. (2015)					x			x		
Caron, Marchet & Perego (1998)				x						
Cheng & Kumar (2015)					x	x				
Elfving et al. (2010)	x						x			
Hamzeh et al. (2007)	x	x								
Ibrahim & Hamzeh (2015)						x				
Jang, Russell & Yi (2003)										
Kalsaas et al. (2011)	x		x							
Lange & Schilling (2015)							x			
Mossman (2007)			x						x	
Ng, Shi & Fang (2009)		x				x				
Nguyen et al (2008)										x
Pinho, Telhada & Carvalho (2008)	x						x			
Said & El-Rayes (2013)			x		x	x				
Said & El-Rayes (2014)					x	x				
Salagnac & Yacine (1999)									x	
Silva & Cardoso (1999)				x						x
Skjelbred, Fossheim & Drevland (2015)		x	x		x		x		x	
Sobotka & Czarnigowska (2005)	x									
Vidalakis, Tookey & Sommerville (2011a)										x
Vidalikis, Tookey & Somerville (2011b)										x
Voigtmann & Bargstädt (2010)						x				
Wegelius-Lehtonen, T (2001)										x

IT support for logistics was highlighted in some form in most papers. BIM-based approaches either used BIM to evaluate optimum or feasible storage areas (Said & El-Rayes 2013; Said & El-Rayes 2014; Cheng & Kumar 2015) or used BIM for site logistics planning or 4D simulations (Bortolini et al 2015; Skjelbred, Fossheim & Drevland 2015). Simulation or optimization based IT solutions included a wide variety of models, for specific simulation of a structural formwork system (Ibrahim & Hamzeh 2015) to simulating several aspects of logistics (Voigtmann & Bargstädt 2010) to optimizing schedules based on logistics (Said & El-Rayes 2013, 2014). Web-based systems for logistics included delivery management systems (Pinho, Telhada & Carvalho 2008; Elfving et al. 2010; Lange & Schilling 2015; Skjelbred, Foosheim & Drevland 2015) and web-based production control systems linked to material management (Arbulu & Ballard 2004; Arbulu et al. 2005).

Other interventions related to logistics were concerned with optimizing inventories or safety stocks (Caron, Marchet & Perego 1998; Silva & Cardoso 1999), using logistics companies to perform transportation on site (Salagnac & Yacine 1999; Mossman 2007; Skjelbred, Fossheim & Drevland 2015) or using standardization or pre-assembly (Arbulu & Ballard 2004, Bortolini et al. 2015). Ngyuen et al. (2008) proposed a new process-based cost modelling system, including the process cost of logistics. Wegelius-Lehtonen (2001) reviewed a set of performance measurement indicators for different company levels (strategic, tactical, operational). Silva and Cardoso (1999) defined different logistics decisions needed on strategic, structural and operational levels. Vidalakis, Tookey & Sommerville (2011a, 2011b) reported analysis related to Builder's Merchants and their profit drivers.

NEW MODEL OF LOGISTICS AND REVIEW OF EMPIRICAL RESEARCH RESULTS

Based on different formulations of logistics problem and solutions, we propose the model in Figure 1 to guide empirical research. Logistics impacts work flow reliability and labor productivity which are both key labor performance metrics in lean construction. Safety stocks, either on-site or in a logistics center, impact work flow reliability (1). However, safety stocks on site decrease the amount of space available (2). The available space is also impacted by storage locations (7) and other work tasks (9) and impacts labor productivity (8). Storage locations close to work performed interfere with productivity (6) but decrease needs for material transfer (3) which can impact productivity of skilled labor if they are responsible for logistics (4). Location of logistics equipment should be connected to storage locations (10) and affects needs for material transfers (5).

Empirical research results on productivity were classified based on the connections in the model of Figure 1 (Table 3). The table further classifies results based on method: simulation, one or more case studies and whether the evidence for results was anecdotal or empirical (measured). In most cases, productivity was not explicitly measured for each connection but as an aggregate measure and the papers just hypothesized cause and effect in their discussion of results.

Most of the papers focus on the impact of delivery on workflow reliability, for example by classifying lack of materials as a root cause of failed plan completion (e.g. Liu & Ballard 2009) or by directly investigating the impact of safety stocks on productivity (e.g. Gonzalez, Gonzalez & Miller 2011). Horman & Thomas (2005) optimized safety stock size based on not having too much or too little inventory. Watkins et al. (2007) simulated the relationships between multiple crews moving through the building but ignored material stockpiles. A few papers discussed several connections but their evidence was anecdotal in nature (Court et al. 2005; Elfving et al. 2010).

Some connections have gained significantly less attention to others. For example storage location and its direct impact on labor productivity due to skilled labor moving materials was mentioned only in three studies and the evidence was anecdotal (Court et al. 2005) or mixed with other factors (Thomas & Sanvido 2000). The impact of storage locations to availability of space and thus to productivity was mentioned in four papers but papers reporting productivity impacts (Court et al. 2005; Elfving et al. 2010) did not separate these impacts from other factors and their evidence was anecdotal in nature. The interface between storage locations and equipment has not been discussed.

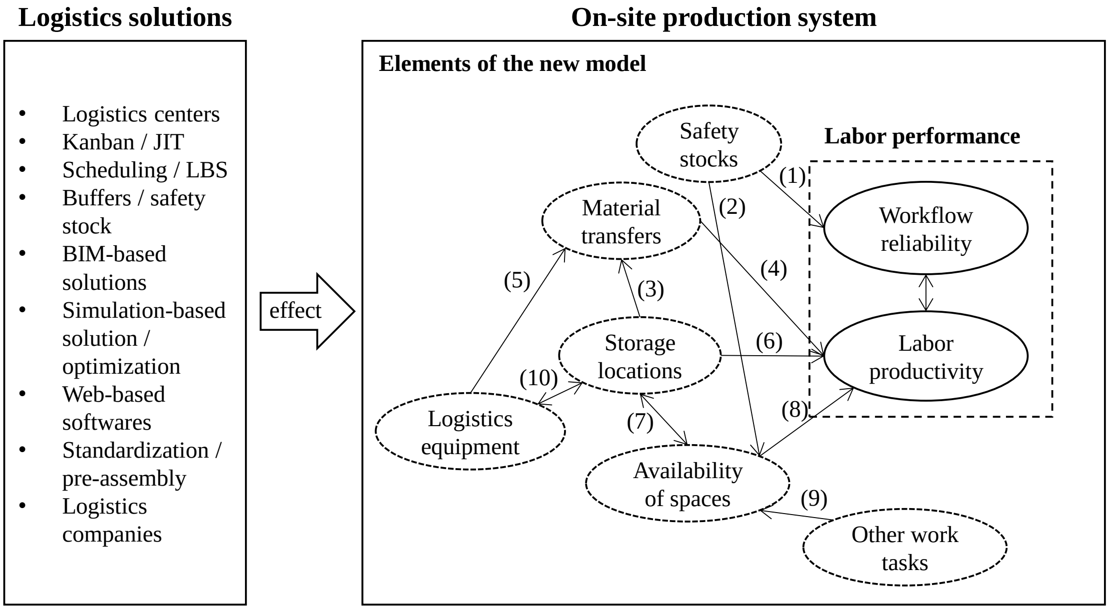

Figure 1: New model of construction on-site logistics

CONCLUSIONS AND FUTURE RESEARCH

Some aspects of logistics, such as delivery reliability, have been extensively studied. Others, such as interference of materials with crews or the impact of storage locations on productivity have received far less attention, confirming our initial hypothesis. Much of the evidence is based on single case studies and several studies are anecdotal in nature. It can be concluded that despite the importance of the topic, we do not know much about the impact of logistics on the performance of production system. We lack tools for making logistics decisions taking into account all the impacted variables.

Future research should focus on filling the gaps of this research in a systematic fashion, for example based on the model presented in this paper. Research should isolate the impact of different factors when possible. For example, the impact of storage location to labor productivity can be isolated by explicitly recording the non-value adding time required to haul materials from storage to installation area. Any interventions and action research should clearly identify which variables they are targeting and their impact should be measured. Simulation can also be a very useful research method.

The limitations of this research include the small amount of search terms used to find literature to review. More relevant papers could be found by using traditional keywords for on-site logistics, for example “materials management”. Regarding productivity, several important papers could be found by searching for the term “waste”. However, it is unlikely that the overall conclusions would change by adding more papers. It is safe to say that research on construction logistics has been very fragmented and a more systematic research approach is required to increase the understanding of this important topic.

Table 3: Empirical results classified by connection

Authors	Method / evidence	Model connections								
		1	2	3	4	5	6	7	8	9
Bortolini et al. (2015)	Case Study / empirical		x		x	x			x	
Bulhoes, Picchi & Folch (2006)	Two case studies / empirical	x								
Court et al (2005)	Case study / anecdotal		x				x	x	x	x
Elfving et al. (2010)	Case study/ anecdotal		x	x	x			x	x	
Gonzalez, Gonzalez & Miller (2011)	Case Study / empirical	x								
Horman & Thomas (2005)	Three case studies / empirical	x	x						x	
Kalsaas et al. (2011)	Case study / empirical				x					
Lange & Schilling (2015)	Case study / empirical				x			x		
Liu & Ballard (2008)	Case study / empirical	x								
Liu & Ballard (2009)	Case study / empirical	x								
Ng, Shi & Fang (2009)	Case study/ simulation				x					
Nguyen et al (2008)	Simulation				x					
Picard (2002)	Case Study	x								
Pinho, Telhada & Carvalho (2008)	Case study/ anecdotal	x						x		
Skjelbred, Fossheim & Drevland (2015)	Case study/ anecdotal	x			x				x	
Thomas & Sanvido (2000)	Three case studies / empirical	x				x	x			
Voigtmann & Bargstädt (2010)	Simulation	x		x	x		x			
Watkins et al (2007)	Simulation								x	x
Zhao & Chua (2003)	Case study / empirical	x							x	

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