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Dynamic Control of Resource Logistics Quality to Eliminate Process Waste in Rebar Placement Work

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Abstract

Output-oriented resource control in the traditional planning methods is still prevalent in construction industry. It frequently causes unpredictable wastes leading to deterioration of the sequenced supply chains. On the other hand, the use of feed-forward control offers the opportunity for prevention by ensuring the high quality of necessary process resources. This paper, in turn, presents a dynamic control approach that highlights the effectiveness of feed-forward control on minimising process wastes. The field experiment in this paper presents the rebar supply and placement on an actual construction site. It aims to measure the responsiveness of pre-controlled resources to ever-changing process performance. Collected data during this field study provided the basic data for establishing statistical relationships between resource logistics quality and process performance. The research experiments found out two of the critical resource logistics: (1) Available number of workers; and (2) Distance between resource and final place. Finally the proactive control on these entities resulted in a dramatic reduction of process waste, leading to the improvement of productive work rate (31.0 to 53.3%). The main contribution of the research lies on the first-hand investigation from a very probable situation, which would benefit practical engineers and construction managers.

Keywords: *process waste, logistics, supply chan management, rebar placement, performance*

1. Introduction

For several decades, quality has been a major focus for various industries to boost their growth (Tang *et al*., 2005; Deming 2000). Today, acceptable product quality is defined as meeting requisite target values within predefined limits set by the customer and/or project participants (Di Mascio and Barton 2001). These values are linked to specific characteristics of the product which are used to establish an inspection protocol to ensure that the process outputs meet defined standards.

As compared to manufacturing with its stable production units and moving Work-In-Progress (WIP) product, construction requires a constant change of process resources while being exposed to uncontrollable conditions, such as soil or weather, thus requiring sophisticated real-time monitoring to achieve a consistent output quality (Flores-Cerrillo and MacGregor, 2004; Al-Bahar and Crandall, 1990; Tah and Carr, 2000). Nevertheless, the main avenue for ensuring quality of construction has been final checks, possibly resulting in expensive repairs.

The research on quality control has followed two approaches: (1) reactive feed-back and (2) proactive feed-forward (Abellan-Nebot *et al.*, 2012). The former method pursues the final quality through inspection, while the goal of the latter is to prepare the quality of process resources that is vitally important to guaranteeing different process outcomes including output quality, labour productivity and material waste. Recently, responding to the aforementioned challenge, the concept of integrating the two has been proposed (Cervin *et al.*, 2002; Thomas *et al*., 2005; Moon *et al*., 2015; Moon *et al.*, 2016a). The strength of this combined system is its capacity to handle even fast-track projects, which are common today. However, the construction industry, until today, uses a feed-back approach to inspect the final quality of products (Barhak *et al.*, 2005). Unfortunately, the prominence of this reactive inspection does not provide a promising method to address the production wastes that originate from undesired process resource quality (Moon, 2014; Moon *et al.*, 2016b).

This paper presents a Dynamic Control model that expands the control capacity of the traditional inspection system. The model aims to reduce process waste by utilising a feed-forward control as the resource planning to improve construction process. The

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quality in this method will be measured by predicting the occurrence and amount of production waste. Referred to as the '*process resource quality*', it allows site logistics to be measured by preparedness of the resource to ensure that the waste is minimized (Moon, 2014; Moon *et al.*, 2015; Moon *et al.*, 2016c). This improvement will be derived from the elimination of process wastes, which can be accomplished by the proactive control on site logistics of process resources.

The contribution of the presented research is to measure the scientific evidence that verifies the effect of a proactive control on process efficiency. The second part of this paper presents the implementation of the dynamic control method on an active construction project, focusing on a rebar supply chain. The objective of this implementation is to quantify the causality between different logistics plans and work performance. The work performance will be measured by the amount of process wastes. The following section firstly reviews definitions of quality, in order to understand this proposed quality method.

2. Literature Review

2.1 Review on the Transition of Quality Definition

Numerous attempts have been made to define the quality in engineering. In order to measure and evaluate it properly, it should be clearly defined first (Webber and Wallace, 2011). The strategy of the control action should be different according to the definition of the quality. After reviewing traditional definitions, a model is developed based on a transitional quality definition to activate a feed-forward control.

From the definition in the previous research publications, quality generally can be measured by the *degree of discrepancy between requirements and actual state*. Thus, inspection of quality is carried out with the help of a checklist that lists the expected measures. When discrepancies are discovered, corrective

Table 1. Literature Reviews on the Traditional Definition of the Quality

Definition Clusters	Sub-Clusters	Extracted Words from Literatures	References
1. Degree of Excellence	1.1 Comparative Advantage	Quality is viewed as a degree of excellence for customer. Quality is defined relative to available and associated alternatives.	Oxford Dictionary; Garvin, 1987; Bagad, 2008; Garvin, 1988; Brown and Seidner, 1998; Mahadevan, 2007; Kerzner, 2009; Mehta, 2004; Smith, 1998; Harry and Schroeder, 2000; Rosenau and Githens, 2011; Tennant, 2001
	1.2 Satisfaction	Products that best satisfy their preferences are those with the highest quality. The first step in quality definition is to study the needs and expectations of the customer. Because quality is dependent on meeting customer's needs. The Kodak definition of quality is the needs and expectations of the customer. Product's ability to satisfy user needs. Quality is a state in which value entitlement is realised for the customer The best definition of quality is considered as customer satisfaction experienced	
2. Absence of Waste/Defects		Quality is viewed as an absence (or elimination) of defects. Quality is defined in terms of costs and prices. The underlying principle of total quality is to provide genuine effectiveness. Acceptable quality must be attaining zero defects. A cost that represents outstanding value meets or exceeds the needs of customer. No more than 1% defective lot: the absence of undesirable characteristics in a product. One of the ways that people judge quality is absence of product defects	Garvin, 1987; Bagad, 2008; Garvin, 1988; Kerzner, 2009; Mehta, 2004; Rosenau and Githens, 2011; Feigenbaum, 1991; Crosby, 1995
3. Requirements and Specifications	3.1 Attributes Management	The quality can be determined by comparing a set of inherent characteristics with a set of requirements. Quality is defined by implication in terms of attributes and some scales used to measure and combine these attributes. Quality is viewed as a quantifiable or measurable characteristic or attribute. Quality is a property that can be ascribed to any entity. Quality is a state in which provider in every aspect of the business relationship. Quality is the degree to which an object (entity) [e.g., process, product, or service] satisfies a specified set of attributes or requirements	Bagad, 2008; Garvin, 1988; Brown and Seidner, 1998; Mahadevan, 2007; Mehta, 2004; Smith, 1998; Harry and Schroeder, 2000; Rosenau and Githens, 2011; Crosby, 1995; Lewis, 2001; Cooper and Fisher, 2002; Baker *et al.*, 2007
	3.2 Designed Requirements and Answered Expectations	Requirements or specification are established by design. Needs and expectations of customer are translated into product and service specification The easiest definition of quality is conformance to specifications. Quality has to be defined as conformance to requirements. Meeting a specification or conformance to specifications. In the past, quality was conformance to specifications, and meeting customer requirements. One of the ways that people judge quality is conformance to standards and policy.	
4. Minimised Variation		Any deviation implies a reduction in quality Quality can also mean the absence of variation in its broadest sense. Higher product quality definition means less variation of a product characteristic.	Garvin, 1988; Bagad, 2008; Mehta, 2004; Ross, 1996
5. Fitness for Use		Quality can be defined as fitness for use. Products created for use by others	Mahadevan, 2007; Smith, 1998

fixes will be needed. Table 1 summarises how twenty scholarly papers defined the quality, and their key points are divided into five clusters: (1) *Degree of Excellence*, (2) *Absence of Waste*, (3) *Requirements and Specification*, (4) *Minimised Discrepancy*, and (5) *Fitness for Use*. It represents five points to define the quality built on the basis of Garvin's work (1984). He suggested eight dimensions of quality: performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality.

The first cluster: the degree of excellence consists of two sub-clusters: (1.1) Comparative Advantage and (1.2) Satisfaction. The discussion in this cluster highlighted that the quality can be measured by its comparison against other aspects of a similar kind or available alternatives. Thus, it is believed that the relative advantage will lead to product satisfaction. The second cluster encompasses the goal that leads to zero waste/defects. They try to attain an acceptable quality via the elimination of waste/defects. Requirements and specifications are also argued as the method for quality measure. The third cluster suggested the inspection of a set of output characteristics that have to be in conformance to predefined requirements/specifications. Finally, the last two clusters describe the minimised variation of the product quality and its fitness for use as the quality measure.

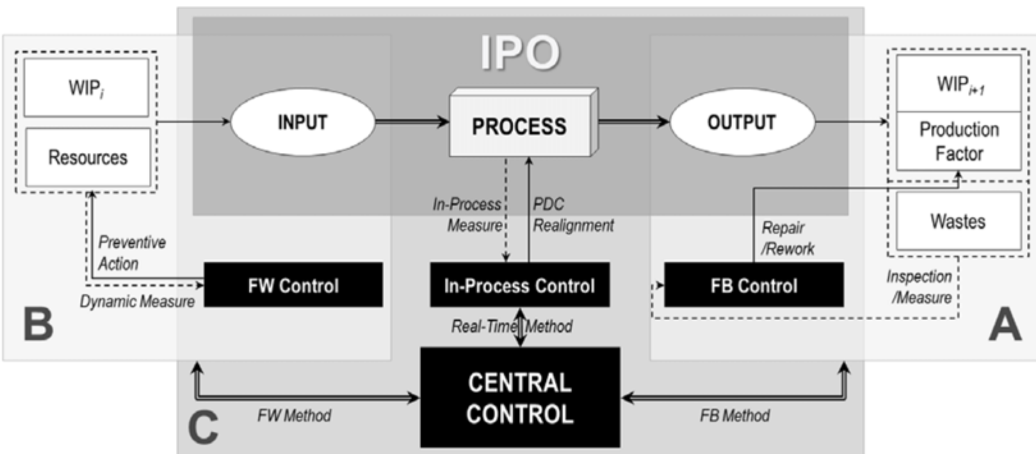
The aforementioned five clusters are based on the feed-back method referred to as an inspection/rework (Shingo, 1986). However, due to the outdoor/on-site nature in construction, the feed-back method for quality assurance often causes costly rework to recover undesired quality products. In this recognition, Bernold (2010) has shown that the lack of effort on process inputs can drastically impact on the productivity, safety and quality of entire operations.

2.2 Process Performance with Two Quality Concepts

The complicated nature of engineering project operations necessitates the need for a high level of constant performance in its resource management (Hou *et al*., 2017). This standard allows the management to coordinate its planning and associated activities, thereby contributing to lower total expenses as well as a reduced variation in resource allocation (Ashuri and Tavakolan, 2011). Nandong (2015) also asserted that "the feedforward controller enables early compensation of a measured disturbance before it can seriously affect the process". In this regard, it is of critical importance to embrace the feed-forward proactive method when undertaking resource planning (Moon *et al.*, 2016b). Conversely, it is necessary to note that the corrective method is not able to completely eliminate the possible occurrence of process waste, which will in turn affect the process performance negatively.

Figure 1 shows an example of inefficient time usage, caused by the corrective method of resource planning. Here, the two crews had no option but to reorder the distribution of long rebar(s) one by one, since they had been organised the wrong way during the preceding process, 'unloading bundles of rebar'. As such, this example indicates one of the possible limitations of traditional resource control. In other words, a proactive control is needed to maintain the designed state of input to reduce the likelihood of production problems in the Input-Process-Output (IPO) framework. This paper presents a research endeavour to test a problem-free process through preventive resource control, leading to other improvements as its synergy effect.

Fig. 1. Unavoidable Waste During Work Preparation



Note WIP: Work-In-Progress; FW: Feed-forward; FB: Feed-back; PDC: Process-centred Dynamic Control

Fig. 2. A Dynamic Control Model for Construction

3. Modelling The Dynamic Control of Process Resources

Figure 2 presents the Dynamic Control (DC) model built around the Input-Process-Output (IPO) framework incorporating the traditional feed-back, feed-forward, and in-process controls represented by Area A, B, and C respectively. The in-process control is referred to a real-time approach to monitor the process continuously. Each control component consists of data collection and correction actions designed to mitigate the gap between actual and target values. The central control, presented in Area C, integrates the in-process control with the feed-back/feed-forward control modules.

The process input of Area B is comprised of the Work-In-Progress (WIP) and resources. Both as a process input have its own quality that will influence process/output. This input is required to be controlled beforehand, as the feed-forward control in DC model. The error represents the gap between the measured and required values of process resource. The communication between the feed-forward control and WIP/resource acts as a preventive loop in that sends action. This proactive control action aims to prevent the possibility of any problems resulting from input quality. Namely, this control is expected to improve not only product quality, but also other managerial targets resulted from the synergy effect of prepared resources. Lastly, control rules are responsible to signal when quality reaches levels that eliminate the risks of undesired outcomes.

The second control module: the in-process control monitors real-time quality during process. Examples are formwork pressure, concrete slump or concrete temperature. The real-time measured value is compared to target value where difference exceeds acceptable threshold values result in the creation of errors. Realignment reduces this discrepancy between actual and target values. After the process, the output is obtained and outlines errors that refer to defects in quality inspection. The output is represented by WIP and the production factors that are the final consequences from the IPO framework. When the defect is observed, the feed-back control (e.g. repair/rework) needs to recover it. Area A in Fig. 2 depicts the mechanism of this feed-back control. The output also contains the wastes as its negative aspect. Finally, the central control collects this data and identifies the causal relationship within the IPO framework for the next process, while supervising the process comprehensively.

Traditional IPO framework focuses on representing the flow of resource over time. The model presented in Fig. 3 enhances it by integrating additional factors important to the performance of the process. It extends a conventional IPO model presented in a previous publication (Bernold and AbouRizk, 2010). The most relevant addition is the feed-forward control as indicated in Area B in Fig. 2, and Fig. 3 presents the selected list of the relevant resources. As depicted, each input group receives a quality descriptors found to be critical to achieving a high quality of the process/output. Furthermore, the process output consists of three categories, WIP, production factor and wastes. One of the core contributions of dynamic control is to achieve the desired quality of these outputs derived from the pre-controlled inputs.

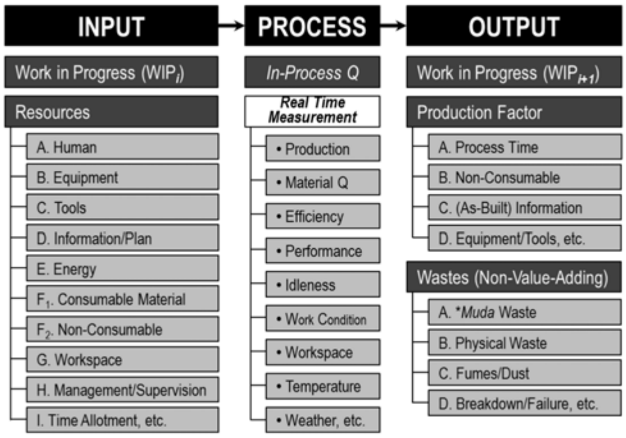


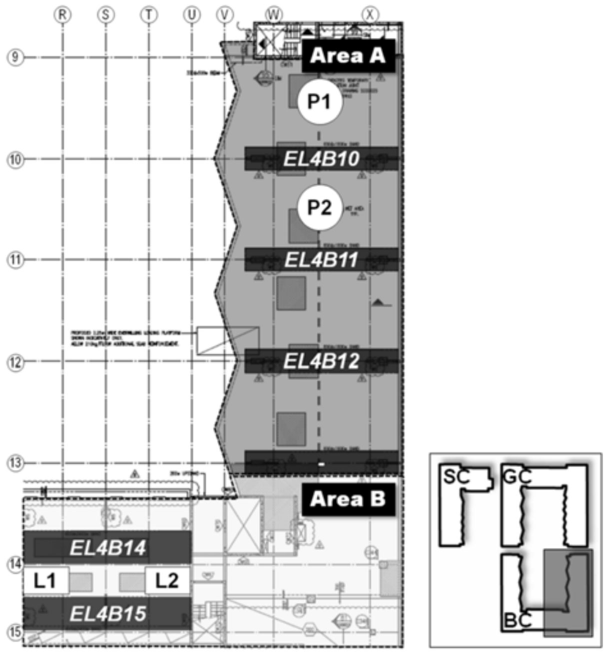
Fig. 3. Quality-based Construction Input-Process-Output Framework

For example, the rebar placement as a process requires a set of inputs and its acceptable level of the process resource quality before launching the process. These inputs include several bundles of rebar delivered by the supplier. To prevent any loss of operation, the central control needs to clarify the future effect of these bundles on the facing process. Based on this causality information, the feed-forward control on critical resource quality is defined. In other words, the bundles of rebar will be arranged beforehand by considering the sequence of process, since any unsuitable process qualities of these bundles will result in substantial amounts of wastes and/or unacceptable production quality.

On the basis of the presented model, the following sections cover field experiments focusing on rebar placement work. The research tests in this paper focus on the causality analysis between consumable material logistics (Input) and process time/relevant Muda wastes (Output). The feed-forward control based on this causal information aims to build up a proactive action to ensure the positive effect of desired input logistics on the minimisation of process wastes, finally leading to the efficient time-spent.

4. Design of the Field Experiments

The field experiment that applied the dynamic control approach is the causality analysis of the resource qualities in the rebar supply and placement work, with the objective being to minimise process waste in the rebar placing operation. The measurement in this testing in turn verified the effect of dynamic control on process waste. The site served as the testing subject is a new accommodation project located in Kensington, New South Wales, Australia, consisting of three high-rise buildings: Seniors Hall College (*SC*), Goldstein & Fourth College (*GC*) and Basser & Baxter College (*BC*). After a discussion with site managers, one of three buildings was selected for this field work: the *BC*



*SC: Seniors Hall College; GC: Goldstein & Fourth College; BC: Basser & Baxter College

Fig. 4. East Sector of Floor Plan on Level 4, Basser & Baxter College Building

building as shown in Fig. 4.

Five beams on level 4 at the east sector of the building were selected for this experiment. Fig. 4 shows the east sector of the floor plan for level 4. P1 and P2 in Fig. 4 refer to the interim storage areas of the delivered rebar from the supplier; these two spots were stocked with several bundles of rebar. From this arrangement, each beam received a different site logistics arrangement of rebar bundles. Considering the adjacency (pick-and-place distance) of the resource, the process of beam 10 (EL4B10) received superior quality logistics as compared to the processes of beam 11 (EL4B11) and 12 (EL4B12).

In order to specify the comparable resource logistics, the observation was required to find out critical variables out of ten resource groups in Fig. 3. Accordingly, five critical variables of the resources were determined on the basis of the initial observation: *available number of workers*, *rebar adjacency*, *rebar weight/length* and *workspace sufficiency*. To facilitate each measurement, the available number of workers needs to be counted during the monitoring of the workers' behaviours. The rebar adjacency (pick-and-place distance) denotes the distance between the storage area and its final placement. The measurement also planned to record the weight and length of the rebar(s) that was being handled by workers. Lastly, according to the working area for each measurement, workspace can be relatively evaluated based on its sufficiency (1: sufficient, 0.5: ordinariness, 0: insufficient). Three beams: EL4B10/11/12 were assigned for this comparative observation.

Furthermore, the work efficiency in the rebar placement work of EL4B10/11/12 was selected as an in-process/output index. This time study is based on previous research (Bernold and AbouRizk 2010). Bernold proposed two methods of measuring labourer performance in construction: (1) Continuous Time Study, and (2) Work Sampling. This study utilises two methods for measuring the steel fixers' work efficiency.

Table 2. Classification of Rebar Placement Work in Construction

	Work Tasks	Classification
A	Direct Work	Value-Adding Effort
B	Carrying tools and materials within the staging area	Contributory Effort
C	Work related communications	Contributory Effort
D	Rehandling with crane	Ineffective Time
E	Measuring and other minor contributory work	Contributory Effort
F	Walking empty-handed	Ineffective Time
G	Searching for rebar	Ineffective Time
H	Obtaining tools and rebar outside the staging area	Ineffective Time
I	Waiting for tools, materials, etc.	Unproductive Time
J	Correcting/replacing rebar	Unproductive Time
K	Idle	Unproductive Time
L	Non-work related communications	Personal Time
M	Reviewing the Drawings	Contributory Effort
N	Not observable	Personal Time

As shown in Table 2, the rebar placement work comprises fourteen specified work tasks (Salim and Bernold 1994). Again, this list is sorted into five classifications, *Value-Adding Effort (VAE)*, *Contributory Effort*, *Ineffective Time*, *Unproductive Time* and *Personal Time*. Among these classifications, *Ineffective Time* and *Unproductive Time* have to be minimised as the process waste, in order to increase the ratio of VAE. On the basis of this list, the data collection/analysis will be accomplished.

Based on the comparison of three beams (EL4B10/11/12), EL4B14 and B15 were designed as the dynamic control-applied process in terms of resource planning. Although all five processes were conducted by a single five-man team over approximately one hour per each process equally, the sequence oriented lay-down (L1 and L2 in Fig. 4) provides more improved resources for workers undertaking rebar placement work, instead of masses of rebar. Finally, the time data verified the effect of this feed-forward control.

In the next section, the comparative analysis specifies the difference in rebar placement works of EL4B10, B11 and B12. A statistical data analysis quantifies the effects of the site logistics on the work efficiency of the steel fixers. Based on this data analysis, the following sub-section describes a modified process in EL4B14 and B15, as the feed-forward control in rebar placement work. Finally, the last sub-section presents the continuous time study to verify the effect of the prearranged rebar resources.

5. Data Collection and Analysis

5.1 Comparative Observation using Work Sampling; EL4B10/11/12

Table 3 summarises the result of the observation in the rebar

Table 3. Work Sampling of Rebar Placing Process for EL4B10/11/12

Work Tasks		Beam 10		Beam 11		Beam 12	
		Total	Percent	Total	Percent	Total	Percent
A	Direct Work	79	39.5%	60	30.0%	54	23.5%
B	Carrying tools and materials within the staging area	2	1.0%	3	1.5%	3	1.3%
C	Work related communications	23	11.5%	15	7.5%	19	8.3%
D	Rehandling with crane	0	0.0%	0	0.0%	6	2.6%
E	Measuring and other minor contributory work	9	4.5%	10	5.0%	9	3.9%
F	Walking empty-handed	15	7.5%	9	4.5%	14	6.1%
G	Searching for rebar	11	5.5%	27	13.5%	37	16.1%
H	Obtaining tools and rebar outside the staging area	5	2.5%	9	4.5%	5	2.2%
I	Waiting for tools, materials, etc.	7	3.5%	14	7.0%	15	6.5%
J	Correcting/replacing rebar	9	4.5%	20	10.0%	9	3.9%
K	Idle	15	7.5%	15	7.5%	21	9.1%
L	Non-work related communications	7	3.5%	10	5.0%	11	4.8%
M	Reviewing the Drawings	13	6.5%	6	3.0%	12	5.2%
N	Not observable	5	2.5%	2	1.0%	15	6.5%
Total		200	100.0%	200	100.0%	230	100.0%

placement work of EL4B10, B11 and B12. Work Sampling was conducted to evaluate the labour performance, and comparative analysis was undertaken according to the different material logistics. The workforce consisted of an eight-member crew with one foreman and seven workers. This experiment resulted in 630 ratings, and configured in Table 3. One of the most critical differences is the Work Task A (Direct Work), which are 39.5% (EL4B10), 30.0% (EL4B11), and 23.5% (EL4B12) respectively. After placing, no defect was detected with the three beams.

Data shows the most notable differences were observed in Work Task A, G, and J. In addition to Table 3, Fig. 5 highlights the comparison with these selected variables. EL4B10 results in the highest rating in Work Task A (39.5%), and this outcome results from relatively low rating in Work Task G (5.5%) and J (4.5%). EL4B11 attains 30.0% in Work Task A. While the rating in Work Task A decreases when compared to the rating during the process of EL4B10, two others (Work Task G and J) increase. They were 13.5% (Work Task G) and 10.0% (Work Task J) respectively. In other words, the steel fixers in EL4B11 spent more efforts/time without adding values. Consequently, it leads to the decrease of the direct work ratio.

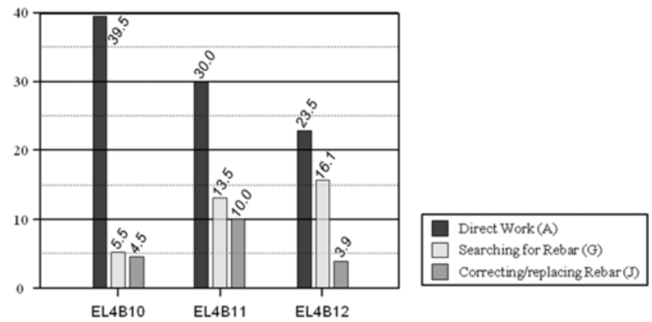


Fig. 5. Beam (X) - Effort Rate % (Y) Graph of the EL4B10/11/12 Processes

EL4B12 showed the lowest rating in Work Task A, 23.5%. This result has a strong causality with the high rating in Work Task G (16.1%). Although Work Task J decreased to 3.9%, the highest rating in Work Task G led to the lowest rating in Work Task A (23.5%) during the reinforcing process of EL4B12. Based on this result, the next section presents the analysis of this causality between resource logistics and work performance, specifically.

5.2 Statistical Analysis of Causal Relationships

In order to understand the cause-and-effect relationship between process resource and work time-spent, a statistical analysis was accomplished. The goal of this analysis is to quantify the effect of different process resource qualities on the work ratings in rebar placement work. Based on this causality information, the process resources can be feed-forward controlled, so that this proactive control will influence on process outcomes as its future effect. The Multiple Regression Analysis (MRA) and correlation

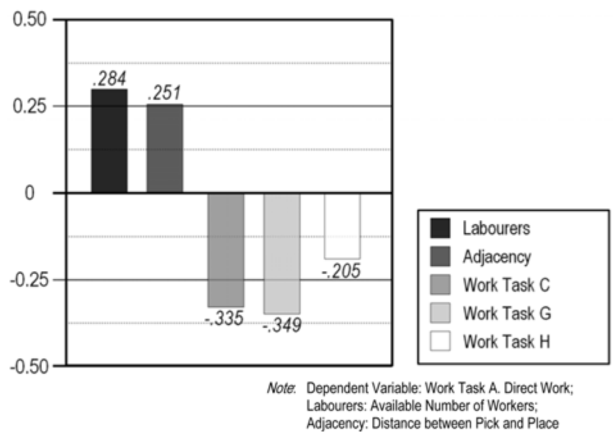


Fig. 6. Standardised Coefficients of Five Significant Variables

Table 4. Correlation Coefficients in EL4B10/11/12 (Moon 2013)

Work Task	(1) Labourers	(2) Weight	(3) Adj	(4) Length	(5) Workspace
A	**.624****	-.223*	**.545****	.010	.254*
B	-.053	-.073	-.126	.109	-.149
C	-.031	-.063	-.008	.250*	-.035
D	-.254*	-.080	**-.368****	.165	-.158
E	-.110	-.037	.071	-.122	.103
F	.108	.134	.132	-.214*	.067
G	-.216*	.281*	**-.342****	**-.317****	-.138
H	-.267*	-.008	.075	-.012	.081
I	-.223*	-.070	-.115	.086	.102
J	.262*	-.047	.079	.043	.128
K	-.119	.139	-.155	-.051	-.200
L	**-.432****	-.050	-.099	-.050	-.062
M	-.116	-.123	.041	.097	-.092

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
(1) Labourers: Available Number of Workers
(2) Weight: Rebar Weight
(3) Adj: Adjacency; Distance between Pick and Place
(4) Len: Rebar Length
(5) Workspace: Sufficiency

analysis were used to find this causality.

In the MRA, Work Task A: direct work is selected as the dependent variable, and others are designated as independent variables. As summarized in Fig. 6, five of the independent variables have significant coefficients (i.e. Significance Level < 0.05). This means that only these five dependent variables statistically have a notable effect on the dependent variable that is Work Task A: direct work. These five variables are *labourers*, *rebar adjacency*, Work Task C, G, and H. The *labourers* have the highest standardised coefficient, 0.284. An equally important variable is the distance between pick and place regarding rebar(s), which is indicated as the *rebar adjacency*. This variable also shows a high standardised coefficient, 0.251. The coefficients for Work Task C, G, and H are -0.335, -0.349, and -0.205 respectively, and the analysis shows that these are expected to affect the direct work negatively. Among them, Work Task G as the most negative process waste should be minimised by priority, to increase the direct work ratio.

Table 4 presents another analysis that aims to reconfirm the interactive relationship by the use of correlation analysis. The *labourers* again were evaluated as the most influent variable on the direct work with the highest correlation coefficient, 0.624. The *rebar adjacency* also had a high correlation coefficient, 0.545. This statistical outcome was shared with the foreman in the rebar placement work, and finally the crew members decided to spend their effort, in advance, to prepare the quality resource logistics in terms of *labourers* and *rebar adjacency* for EL4B14 and B15. In sequence, the effect of this feed-forward control is analysed in the next section, during their rebar placement work.

5.3 Dynamic Control of Resource Logistics; EL4B14/15

As inferred from the process of EL4B10/11/12, the *labourers* and *rebar adjacency* have a significant impact on work efficiency during rebar placement. In consideration of this observation, the material resources for EL4B14 and B15 were planned differently. Firstly, as compared to the previous process (EL4B10/11/12), the majority of the required rebar was intentionally pre-staged (L1 and L2 in Fig. 4) next to the final placement before the work began, as shown in Fig. 7. In the event of absence of required rebar(s), the foreman visited the interim storage place, P1 and P2 in Fig. 4. His supporting actions aimed to allow other workers to focus primarily on the *value-adding effort*. Consequentially, they were able to maintain a suitable condition of *rebar adjacency* over the process.

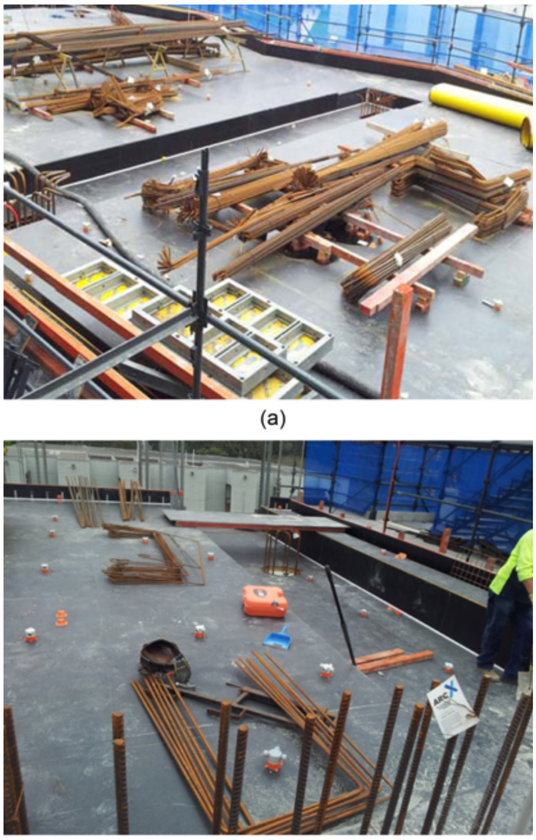

(a)
(b)

Fig. 7. Comparative Process Resource Qualities: (a) Traditional Resources for EL4B10: (b) Pre-Modified Resources for EL4B14

Furthermore, the rebar, which was neatly arranged at L1 and L2, enabled workers to easily identify the required rebar in sequence. This modified rebar logistics resulted in a minimum level of process waste and brought considerable improvements to the process outcome. In addition, to maintain more *available number of workers*, they also organised the proper division of labour. In this manner, two workers were assigned for each beam, with the fifth acting as a foreman monitoring both beams. Within each group, one individual focused on the direct work intensively, while the second worker acted as his assistant. Again, the foreman who was involved in both beams supported

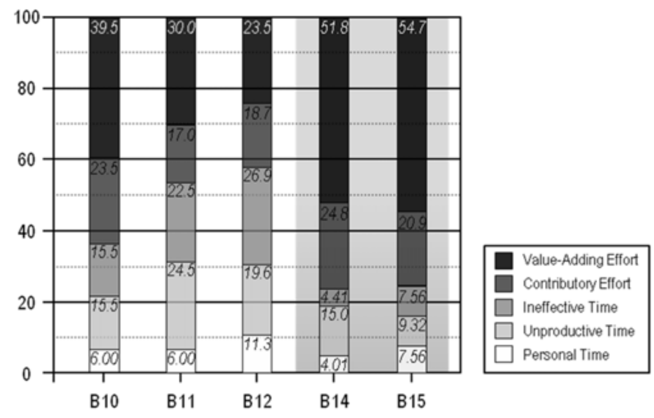


Fig. 8. Beam (X) - Effort Rate(Y) Graph

the other four as needed.

Figure 8 highlights the increased ratio of *VAE* in EL4B14 and B15, compared to EL4B10/11/12. The ratio was measured as 51.8% (EL4B14) and 54.7% (EL4B15) respectively. In addition, the measurements in EL4B14 and B15 showed a decreasing tendency in the ratings of both the Ineffective Time and the Unproductive Time. In the case of EL4B14, the Ineffective Time was 4.41% and the Unproductive Time was 15.0%. The rate in EL4B15 also showed low levels in both, 7.56% and 9.32% respectively. The feed-forward control of process resources led to the increase of direct work ratio by the reduction of the process waste. The following section presents a continuous time study to specify this positive effect by the feed-forward control.

6. Discussion and Validation of the Field Tests

This section describes the interpretation of the continuous time study observing the work effort of five steel fixers (Worker #1-5) during the work for EL4B14 and B15. The collected data provides detailed information about their consecutive performances. It finally was compared to four previous works from (Moon *et al*., 2015); and (Salim and Bernold, 1994), as the brief external validation of the tests. Again no defect was detected after the completion.

Figure 9 displays the result of the continuous time study of Worker #1-5. In order to show the effect of the proactive control (*available number of workers*), the total work time is broken into seven phases. The phases were divided according to the sequenced supportive effort of Worker #3. A feed-forward planning preventively has been made to nominate Worker #3 as a supporter, so that the reinforcing processes of two beams were able to secure at least four work crews continuously. Namely, Phase 2, 4 and 6 were supported by Worker #3 letting other four concentrate on each task. Worker #3 spent these work phases to

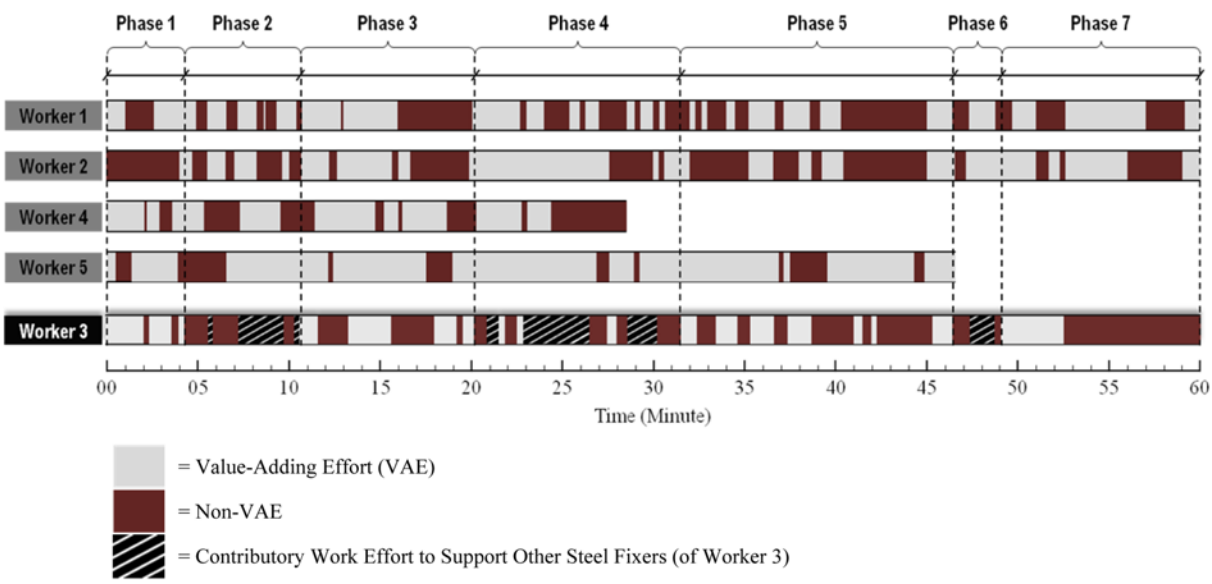


Fig. 9. Continuous Time Study of Five Steel Fixers

Table 5. Fluctuations of Direct Work Ratio (%)

Task	Steel Fixer	Overall	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7
EL4B14	Worker 1	51.9	48.8	49.6	51.6	54.9	41.8	56.3	63.7
	Worker 2	51.7	7.69	43.6	79.6	78.5	35.3	18.8	52.2
EL4B15	Worker 4	56.5	73.8	48.8	69.1	40.9	-	-	-
	Worker 5	79.7	66.5	64.4	82.6	92.1	78.9	-	-
Average		60.0	49.2	51.6	70.7	66.6	52.0	37.6	58.0
Supporter	Worker 3	35.1	82.3	0.00	57.0	9.63	47.3	0.00	36.1

Table 6. Four Previous Works for External Validation (%)

	Work M1	Work M2	Work S1	Work S2
Direct Work	35.6	27.4	24.8	27.8
Process Waste	42.3	48.7	41.4	35.2
Contributory Effort	18.7	18.3	22.2	25.9
Personal Time	3.4	5.7	11.6	11.1

Note: Work M1 & M2 studied by (Moon *et al.,* 2015); and Work S1 & S2 by (Salim and Bernold, 1994)

support others in order to sustain at least four available workers over the total work time.

Table 5 summarises the measured direct work ratio in seven phases for each worker. As designed, Worker #3 showed considerably low direct work ratio during Phase 2, 4 and 6 when supporting others. Although his direct work ratio was just 35.1%, four other steel fixers in EL4B14 and B15 were able to achieve a high ratio of the direct work: 60.0% as the average. In addition, the four workers except Worker #3 were able to show very stable work performances by maintaining high direct work ratio during whole time. This result means that the supportive effort of Worker #3 was available to minimise the non-VAE of other four workers. Thus, this reduction of the process waste led to stable high performance of the rebar placement work in both beams.

Compared to the EL4B10/11/12, much higher ratio of direct work was measured in EL4B14/15. Especially, it was observed that the prearranged rebar(s) in EL4B14/15 significantly decreased the Work Task G (Searching for rebar), from 11.7% to 3.69%, which was statistically analysed as the most negative variable to the direct work. Consequently, this sort of reduction of the process waste resulted in the improvement of direct work ratio. When compared to other previous studies: Work M1&2 and S1&2 presented in Table 6, EL4B14/15 again shows much improved performance in their direct work measurements. The following section summarises and concludes the presented research work.

7. Conclusions

Traditionally, quality control in construction relies on the final inspection of the completed work, thus embracing the feed-back type approach. Of course, inspection naturally defers the quality assessment until the production process is completed, thus overlooking countless opportunities to prevent poor production quality caused by inadequate and even deficient resources. This paper proposed a quality control model, the Dynamic Control, which integrates not only product and production quality but also focuses on feed-forward rather than feed-back control principles. The paper then discussed the effects of experimental field tests incorporating the dynamic control model.

An ideal test-bed for dynamic control was the supply of rebar for final assembly at its final destination. Hence, the comparative field study focused on observing and measuring rebar placement work for five deck beams of a reinforced concrete building. During the first step, time studies were conducted on the placement work for three beams. As expected, the collected data quickly highlighted the drastic effect of quality regarding logistical preparation onto the direct work ratio, with the latter ranging from 23.5% to 39.5%.

The statistical analysis of the collected data underlined the criticality of the number of productive steel fixer (*available number of workers*) with a standardised coefficient of 0.284 and the distance or adjacency of the staged rebar (*rebar adjacency*) with 0.251. Three specific unproductive and wasteful work-related activities, out of thirteen work tasks, showed large negative correlations to direct work ratio: 1) *Work related communications* (-0.335), 2) *searching for rebar* (-0.349), and 3) *obtaining tools and rebar outside the staging area* (-0.205).

The second step of the study utilised these results to design an experiment that applied the principles of dynamic control for the rebar placement work in the remaining two beams. The comparison of the observations highlighted the importance of proactive planning and control on work efficiency. The largest contributor to the improvement of direct work ratio was the amounts of minimised measurement of the *searching for rebar* (3.69%). Consequently, the direct productive work increased by 22.3%, from 31.0% (EL4B10/11/12) to 53.3% (EL4B14/15).

The outcome confirms previous studies proving the positive effect of detailed planning on work efficiency, even though this study focused solely on the process quality of the rebar resource. It is thus recommended to test the efficacy of the dynamic control model by including a larger segment of the supply chain and, of course, other resource streams. The resources include the ten types defined in Figure 3, where interference was an issue. As such, this presented research has the potential to be extended, with the next endeavour focusing on the interference between consumable material/s (rebar), workspace, and time allotment.

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