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Optimizing Concrete Mattress Fabrication Through Lean Project Management: A Value Stream Mapping Approach to Lead Time Reduction

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ABSTRACT

This study aims to minimize waste in the Fabrication Service of Concrete Mattress project and provide control recommendations to minimize delays in the project. This study uses the Lean method and the Critical Chain Project Management (CCPM) method, where the Lean method is used to identify waste with tools such as Work Breakdown Structure, Value Stream Mapping (VSM), Value Stream Analysis Tool (Valsat), Root Cause Analysis (RCA), and Risk Matrix. Meanwhile, Critical Chain Project Management is used to control project time to prevent delays. The results of the study obtained a Lead Time of 89 days with a Process Cycle Efficiency (PCE) value of 65.17%. To identify the factors causing waste, RCA and risk management analyses were conducted. The cause of critical waste was the formwork dismantling method, which fell into the extreme category. The first alternative was to change the formwork dismantling process by using wheels and 150x75 C-channels as rails, which would reduce the time needed to dismantle and reassemble the formwork. The second alternative is to provide buffer time using the Critical Chain Project Management (CCPM) method. After scheduling with CCPM, a time acceleration of 10 days was achieved, from the initial lead time of 89 days to 79 days with a buffer of 10 days, with a PCE value of 73.42%. There was an increase in process effectiveness of 8.25%.

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1. INTRODUCTION

Construction projects have different characteristics that require different handling compared to the management of ordinary service work. These projects require good management in planning and controlling project activities so that they are in accordance with the predetermined schedule (Faiizuddaroini et al., 2022). Buffers are applied in project activities to anticipate uncertainties (Tan, 2011) such as weather conditions, natural disasters, material delays, and equipment damage (Sahrupi et al., 2021). Project management is important in construction projects to support the achievement of company goals and minimize the risk of project failure by managing resources effectively.

The Fabrication Services of Concrete Mattress project, in accordance with the contract with the project user, has a project completion duration of 89 days. Based on the progress report in week 11, the planned project progress was 92.17%, but the actual progress was 68.09% (Fig.1). From this data, there is a gap of 24.09% between the planned progress and the actual progress in the field, with a delay of 21 days. This delay will cause subsequent processes to be postponed and require workers to work overtime to meet the delivery schedule for goods, resulting in actual man-hours exceeding those planned. It indicates that there is waste occurring in the Fabrication Services of the Concrete Mattress project.

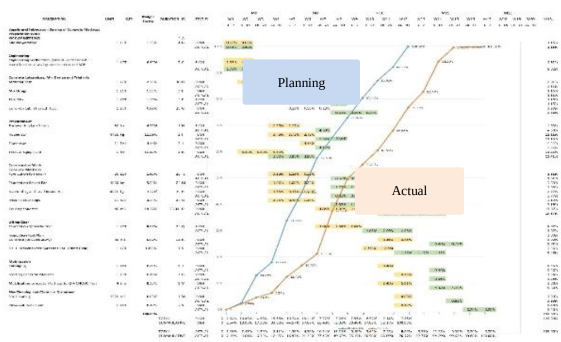

Fig. 1. S-curve fabrication services of a concrete mattress

To overcome these obstacles, a lean thinking approach is needed, known in project management as Lean Project Management (LPM), which contains principles that can be applied to the implementation of construction projects. Lean Project Management is a work method that focuses on processes. This Lean Project Management method combines the Critical Chain Project Management (CCPM) method for scheduling and lean tools for identifying waste and its causes, so that there are no delays and cost overruns in project implementation (Ho et al., 2022).

Critical Chain Project Management (CCPM) is a scheduling management method that focuses on balancing resource availability and providing buffers to anticipate uncertainties (Ma et al., 2014). This resource balancing requires a structured approach to ensure that the project runs smoothly (Nugroho et al., 2020). Buffer time is used to anticipate uncertainties by eliminating multitasking and addressing uncertainties and variations in construction project activities (Bakry et al., 2016; Russell et al., 2014).

Toyota introduced the concept of lean to identify and eliminate activities that do not add value (Liker & Morgan, 2006). The application of lean in projects aims to complete projects on time, obtain good quality, and stay within the predetermined budget (Tan, 2011). Research results show that the application of lean project management can improve work schedules (Ballard & Tommelein, 2012) and reduce project costs (Amran et al., 2019). This study aims to analyze the activities of the Concrete Mattress Fabrication Services Project so that the waste that occurs can be identified and a comparison can be made between the project completion schedule using the CCPM method and the actual project completion, as an evaluation and improvement of the schedule in order to reduce delays in future projects.

2. RESEARCH METHODS

This study uses lean project management stages to evaluate the activities of the Concrete Mattress Fabrication Services Project. The concept of lean in project activities is used to obtain more efficient activities (Lalmi et al., 2021) and produce more cost-effective values (Babalola et al., 2019). The steps in Lean Project Management analysis are big picture mapping, waste workshop calculations, VALSAT (Value Stream Analysis Tools), waste analysis with selected tools, root cause analysis, and CCPM.

This study adopts the Value Stream Mapping (VSM) concept to identify value-added (VA) and non-value-added (NVA) activities (Klimecka-Tatar & Ingaldi, 2020). VSM consists of two types of visuals that can help make improvements, namely the Current State Map (CSM), which is a value stream configuration using icons and terminology to identify waste and areas for improvement, and the Future State Map (FSM) as a blueprint for future lean transformation after identifying and eliminating waste (Herudi et al., 2020). Big Picture Mapping - Current State is information about the flow of information and physical processes of a project, presented in a diagram.

The waste workshop calculation was carried out by distributing questionnaires to several correspondents responsible for implementing the Fabrication services of the concrete mattress project in an effort to identify and describe the waste found in the concrete mattress manufacturing process. From the questionnaire results obtained, a tool selection matrix was compiled using VALSAT (Value Stream Analysis Tools) as a determinant of the tools to be used next to analyze the waste that occurs in the concrete mattress manufacturing process. The waste was then analyzed using the tools determined using VALSAT.

Root cause analysis was used to group the possible causes of a specific effect and then separate the root causes. In this study, the 5-whys analysis method was used to find the root cause because it was considered the most appropriate for the problems in the company.

CCPM is an approach that focuses on the availability of human resources by managing tasks based on predecessor activities and productivity (Anastasiu et al., 2023). CCPM for planning project activities can be timely with the application of buffers to minimize uncertainty (Peng & Peng, 2022). The stages of the CCPM method are:

a) Creating a project network
   Creating a project network by looking at the interrelationships between each activity.
b) Identifying the critical chain
   Identifying the critical chain, which is the longest chain that has activity and/or resource relationships.
c) Input the project buffer
   In creating a project buffer time, find the project buffer and the feeding buffer. The duration of the project buffer and feeding buffer is obtained by performing calculations using the Root Square Error Method (RSEM).

$$2\sigma = 2x\sqrt{\left(\frac{S1-A1}{2}\right)^2 + \left(\frac{S2-A2}{2}\right)^2 + \cdots + \left(\frac{Sn-An}{2}\right)^2} \quad (1)$$

   where 2σ: Buffer size; S: Pessimistic time, and A: Optimistic time.
d) Buffer Zone Identification
   Buffer zone identification is the level of buffer usage. In determining the buffer zone, the author uses a buffer zone indicator that serves to control buffer consumption so that the company can decide what actions to take.

3. RESULTS AND DISCUSSION

The concrete mattress fabrication services project consists of several activities, including a kick-off meeting, engineering verification, concrete laboratory, procurement, fabrication, installation and assembly, concrete pouring, and concrete mattress mobilization. The project begins with a kick-off meeting, which serves to align the owner and contractor's perceptions of the project specifications and objectives. The project ends with the mobilization process, which involves delivering the concrete mattress to the owner's site.

3.1. Work Breakdown Structure

Project activities must be grouped based on a structure diagram called the Work Breakdown Structure (WBS) system. The WBS will show all project activities, which will later be used as a basis for determining activity duration, project costs, and scheduling. The fabrication services for concrete mattresses consist of 13 detailed activities (Table 1).

3.2. Waste Identification

Waste identification was carried out by distributing questionnaires to two respondents who were knowledgeable and responsible for the details of the concrete mattress fabrication services project process,

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namely the project manager and field supervisor. The assessment of the weighting of waste that occurred was expected to clearly map the project waste. The weighting criteria are scores for each type of waste ranging from 0 to 5, with a minimum score of 0 and a maximum score of 5. The higher the waste score, the more frequently the waste occurs. The questionnaire results show that the types of waste with the highest weightings are motion waste, waiting, and defective products (Table 2).

Table 1. Time and Activity Data

No	Activity	Duration (Days)	Predecessor
1	Kick-Off Meeting	1	
2	Site Preparation	4	1
3	Engineering Verification	7	1
4	Concrete Laboratory, Mix Design, and Trial Mix	14	3
5	Procurement	2	4
6	Fabrication formwork	17	5
7	Fabrication Round Bar	18	5
8	Fabrication Fibber Rope	18	5
9	Installation and Assembly Formwork, round bar, and Fiber rope	31	6;7;8
10	Pouring concrete	10	9
11	Lifting Gear	20	5;6
12	Inspection Test Plan	14	10;11
13	Mobilization	6	10;12

Table 2. Questionnaire Data

No	Type of Waste	Score		
		Project Manager	Field Implementer	Total
1	Motion Waste	4	4	8
2	Waiting	3	2	5
3	Defect Product	2	2	4
4	Over Production	0	0	0
5	Transportation	0	0	0
6	Inventory	0	0	0
7	Over Processing	0	0	0
	Total	9	8	17

3.3. *Big Picture Mapping*

Big Picture Mapping (BPM) provides information about the flow of information and physical processes in a diagram (Fig. 2). The production lead time is 89 days (from start to delivery of the product to the owner), and the VA (Value Added) is 58 days. Activities that are classified as NVA (Non-Value Added) and NNVA (Necessary but Non-Value Added) total 52 days. The results show a Process Cycle Efficiency value of 65.17%.

3.4. *Value Stream Analysis Tools (VALSAT)*

The results of the waste workshop calculations yielded the following percentages from the production process: over-processing waste of 0%, motion waste of 47.06%, defective product waste of 23.53%, overproduction waste of 0%, transportation waste of 0%, inventory waste of 0%, and waiting waste of 29.41% (Table 3).

Table 3. Summary of questionnaire 7 waste

No	Waste Type	Total	Average	%	Rank
1	Motion Waste	8	4.00	47.06%	1
2	Waiting	5	2.50	29.41%	2
3	Defect Product	4	2.00	23.53%	3
4	Over Production	0	0.00	0%	4
5	Transportation	0	0.00	0%	4
6	Inventory	0	0.00	0%	4
7	Over Processing	0	0.00	0%	4
	Total	17		100%	

The questionnaire results were used to compile a tool selection matrix using VALSAT as the determinant of the tools to be used next to identify waste occurring in production. The results of the calculation with VALSAT showed that process activity mapping had the highest score of 60.5.

Process Activity Mapping (PAM) is used to analyze each activity and classify it based on NA, NVA, and NNVA (Kurniawan & Rochmoeljati, 2022). This classification aims to identify and minimize waste (Mikkelsen et al., 2022). The grouping results show that the total value-added time is 108 days, with a percentage of 65.06% and the total necessary but non-value-added time is 58 days, with a percentage of 34.94%. Meanwhile, activities that are included in value added have a percentage of 61.54% and activities that are necessary but non-value added have a percentage

Table 4. VALSAT calculations

Type of Waste	Average	Process Activity Mapping	Supply Chain Response Matrix	Production Variety Funnel	Quality Filter Mapping	Demand Amplification Mapping	Decision Point Analysis	Physical Structure Overproduction
Over Production	0.00	L (0)	M (0)		L (0)	M (0)	M (0)	
Waiting	2.50	H (22.5)	H (22.5)	L (2.5)		M (7.5)	M (7.5)	
Transportation	0.00	H (0)						L (0)
Defect Product	2.00	L (2)	L (2)		H (18)		M (6)	
Inventory	0.00	M (0)	H (0)	M (0)		H (0)	M (0)	L (0)
Over Processing	0.00	H (0)		M (0)	L (0)		L (0)	
Motion Waste	4.00	H (36)	L (4)					
Total		60.5	28.5	2.5	18	7.5	13.5	0
Rank		1	2	6	3	5	4	7

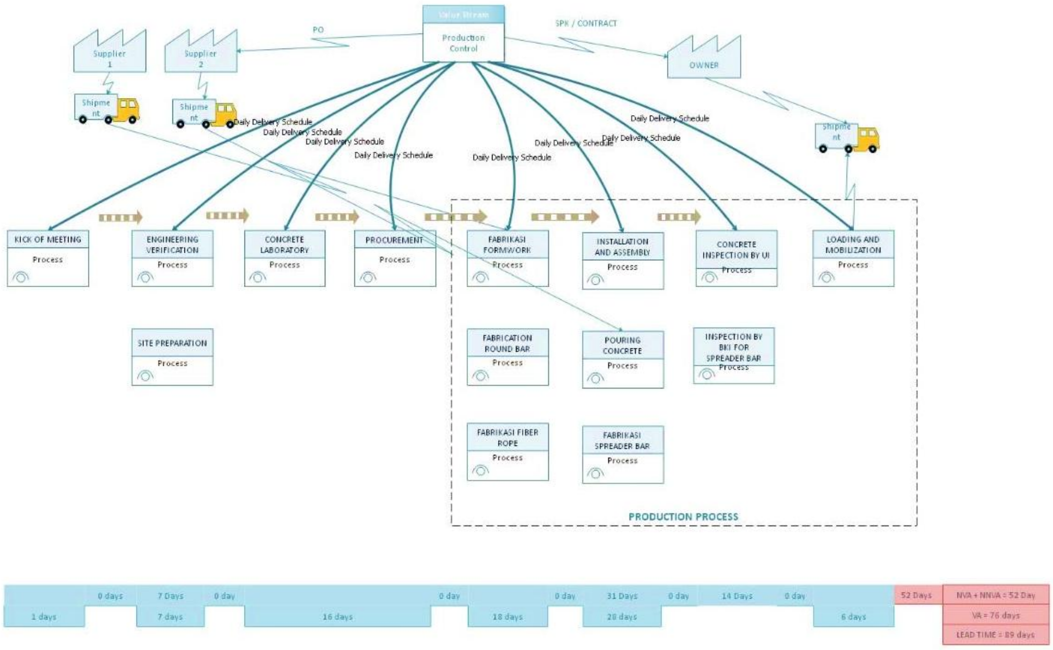

Fig 2. Big picture mapping

Table 5. Percentage of activity categories for all activities

No	Activity	Category	Time (Days)	Time (%)	Activity (%)
1	Site Preparation	NNVA	58	34.94%	38.46%
2	Engineering Verification	NNVA			
3	Procurement	NNVA			
4	Installation and Assembly Formwork, round bar, and Fiber rope	NNVA			
5	Inspection Test Plan	NNVA			
6	Kick-Off Meeting	VA	108	65.06%	61.54%
7	Concrete Laboratory, Mix Design, and Trial Mix	VA			
8	Fabrication formwork	VA			
9	Fabrication Round Bar	VA			
10	Fabrication Fibber Rope	VA			
11	Pouring concrete	VA			
12	Lifting Gear	VA			
13	Mobilization	VA			

of 38.46% (Table 5). To support the smooth running of the production process, after consulting with the project Manager, some activities or times are included in the necessary but non-value-added activities that can be minimized.

3.5. Root Cause Analysis

Root Cause Analysis (RCA) is an approach used to identify the causes of failure in a problem (Doskočil & Lacko, 2019) to identify the relationship between problems and provide effective and sustainable solutions (Janíček, 2017). The tools used to identify problems are the 5-whys analysis to identify the fundamental causes and provide solutions so that they do not recur (Wieczerniak et al., 2017).

Brainstorming activities involve experts (Project Managers and Field Implementers) to identify the causes of critical waste problems. The brainstorming results showed that each type of waste had sub-types of waste, and each sub-type of waste had root causes (Table 6).

1. Waste waiting, with the sub-type of waste being the late arrival of the primary raw materials
   If the raw material procurement process does not comply with the specified time, it will cause delays. The length of the raw material procurement process is caused by the length of time it takes to find suppliers. This is because the raw material supplier database is not well managed, resulting in the company using an outdated and updated database.
2. Waste defect with sub-waste uneven concrete surface
   If the casting process is not dense enough, it will cause rework to cover holes in the uneven concrete

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Table 6. *5*-whys analysis

Waste	Sub waste	why 1	why 2	why 3	why 4	why 5
Waiting	Delays in the arrival of key raw materials	Lengthy raw material procurement process	Lengthy process of searching for raw material suppliers	Outdated supplier database	Lack of supplier database management	
Defect Product	The surface of the concrete mattress is uneven	The casting process is not dense enough	The operator is not skilled enough	Lack of operator expertise		
			The vibro machine is not working properly	The vibration of the vibrator machine is not strong enough	Lack of maintenance of the vibrator machine	
Motion Waste	The number of steps required by workers when dismantling formwork	Too much work dismantling scaffolding poles	Manual dismantling of formwork	Dismantling scaffolding one by one	Heavy formwork and concrete mattress loads	Formwork dismantling method

surface. This problem is caused by two things namely, workers who are not careful with the density of the concrete due to their lack of expertise, and vibrator machines that do not function properly, namely, the machine vibrations are not strong enough due to a lack of control over the vibrator machines.

3. Waste motion with sub waste many work steps for workers when dismantling the formwork
If there is too much dismantling of scaffolding poles, it will cause delays. This is because the dismantling is done manually, one pole at a time, due to the heavy weight of the formwork. This is caused by the formwork dismantling method taking too long.

In determining the priority of the root causes of waste, the tools to be used are risk management. By using a risk management approach, the team is able to take positive steps to minimize the consequences of the root causes of waste. One method commonly used in qualitative assessment of the root causes of waste is the impact probability matrix.

Impact is the effect caused by the root causes of waste in project implementation. The root causes of waste are identified based on the RCA table for critical waste, as well as the impact of the root causes of waste that occur (Table 7).

After identifying the root causes of waste, an assessment of the root causes of waste is carried out. The parameters assessed are the probability of the root causes of waste occurring and the impact of the root causes of waste on a scale of one to five. The description of the probability assessment (Likelihood) ranges from 1-5, namely rare, unlikely, possible, likely, and almost certain. Meanwhile, the impact assessment (Impact) ranges from 1 to 5, namely insignificant, minor, moderate, major, and catastrophic. The root cause of waste in the Fabrication Service of Concrete Mattress project, which is categorized as extreme risk (in the red zone), is root cause of waste no. 4 with a value of 20, namely the formwork dismantling method, with a likelihood value of 4 and an impact value of 5 (Table 8).

Table 7. Impact of root causes of waste on projects

No	Root Causes of Problems	Impact
1	The supplier database is not well managed	Unemployed workers
2	Lack of operator skills	Addition of finishing materials
3	Lack of vibrator machine maintenance	Addition of finishing processes
4	Formwork dismantling methods	The production process takes longer

The root cause waste assessment matrix has four types of zones, namely the green zone, yellow zone, brown zone, and red zone. The green zone is described as low on a scale of 1-4, meaning it is still acceptable and does not require specific resources, only routine management and monitoring. The yellow

Table 8. Waste root cause assessment form

No	Root Causes of Problems	Likelihood Level	Score	Impact Level	Score	Score	Category
1	The supplier database is not well managed	Possible	3	Moderate	3	9	Moderate
2	Lack of operator skills	Possible	3	Major	4	12	High
3	Lack of vibrator machine maintenance	Likely	4	Major	4	16	High
4	Formwork dismantling methods	Likely	4	Catastrophic	5	20	Extreme

Table 9. Risk matrix

		Rare (1)	Unlikely (2)	Possible (3)	**Likely (4)**	**Almost Certain (5)**
Consequence / Impact	Catastrophic (5)	5	10	15	20 Longer production process	25
	Major (4)	4	8	12	16 Lack of maintenance of vibrator machines	20
	Moderate (3)	3	6	9 The supplier database isn't well-managed.	12 Lack of operator skills	15
	Minor (2)	2	4	6	8	10
	Insignificant (1)	1	2	3	4	5

zone is described as moderate on a scale of 5-11, meaning it is still acceptable because it does not cause damage and does not threaten the efficiency and effectiveness of activities. The brown zone is described as high on a scale of 12-16, which is generally unacceptable because it can cause damage, disruption, or control violations. The red zone is described as extreme on a scale of 17-25, which is unacceptable because it can threaten the sustainability and effectiveness of company activities, both financially and politically (Table 9).

Table 10. Alternative development

Root Causes of Problems	Alternatives
The supplier database is not well managed.	Manage the supplier database by updating supplier data more frequently.
Lack of operator skills	Provide training to workers.
Lack of vibrator machine maintenance	Perform regular machine maintenance using a checklist of tools before use.
Formwork dismantling methods	Change the formwork dismantling process by using tools to speed up the process.

Alternative development is used to respond to the root causes of waste and provide alternative policy analysis for improvement to reduce waste and increase efficiency (Table 10). Several alternative solutions to the root causes of extreme waste are:

a. Changing the dismantling process by using tools
   At the beginning of the project, the factors involved in the formwork dismantling process were not considered. After the initial casting, the formwork dismantling process took a long time. Therefore, it was necessary to change the formwork dismantling steps, which were initially dismantled one by one, by attaching wheels to the bottom of the formwork and then placing CNP 100 x 50 iron on the wheel track as a rail. It would cut the time needed to dismantle and reassemble the formwork.
b. Allocation of buffer time
   By using the CCPM method, the company will obtain buffer time that can be used if the project shows signs of delay. Buffer time is additional time given at the end of the project to maintain the security of the project time estimate. Through monitoring of its use, the company will know what actions to plan if the buffer time is used up.
c. Performing regular machine maintenance
   Vibrator machines are important tools during the concrete pouring process. Therefore, the company must create a checklist of equipment to be used during preparation before pouring so that any sudden equipment malfunctions can be immediately identified.

3.6. Critical Chain Project Management

The process of creating a schedule for CCPM implementation is based on project activity data (Table 1). Project activities included in the critical path are activities with codes 1 – 3 – 4 – 5 –7 – 8 – 9 – 10 – 12 – 13, and project activities that are not part of the critical path are activities 2 – 6 – 11.

The next step is to apply the cut & paste method. The cut & paste method can be applied by reducing the activity time by 50%, 30%, 20%, and 10%. The cut & paste method used has a probability of 30%. This 30% probability is used because in the previous project planned by the company's planning department, it was feasible, and the results were in line with the target. In the process of applying the cut & paste method, the normal time of the project activities is reduced by a probability of 30%. The following are the results of the project time reduced by a probability of 30%.

The results of applying the cut & paste method show that the reduction in duration has a decimal point. In the calculation, rounding up is done because excess working time will be rounded up to one day (Table 11). After obtaining the results of the activity times by applying the cut & paste method, the author held discussions with the person in charge of the project. This discussion was conducted so that the planned time would match the estimated actual time of the project activities or the time required for the work in the field. This time consistency is expected so that the company's planning and the execution of project activities in the field are in agreement so that the project can achieve its targets and there are no delays.

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Table 11. Cut & paste method

No	Activity	Duration (Days)	Category	Predecessor	Probability 30%	Time - 30%	CCPM Time
1	Kick-Off Meeting	1	VA		0.3	0.7	1
2	Site Preparation	4	NNVA	1	1.2	2.8	3
3	Engineering Verification	7	NNVA	1	2.1	4.9	5
4	Concrete Laboratory, Mix Design and Trial Mix	14	VA	3	4.2	9.8	10
5	Procurement	2	NNVA	4	0.6	1.4	2
6	Fabrication formwork	17	VA	5	5.1	11.9	12
7	Fabrication Round Bar	18	VA	5	5.4	12.6	13
8	Fabrication Fibber Rope	18	VA	5	5.4	12.6	13
9	Installation and Assembly Formwork, round bar, and Fiber rope	31	NNVA	6; 7; 8	9.3	21.7	22
10	Pouring concrete	10	VA	9	3	7	7
11	Lifting Gear	20	VA	5; 6	6	14	14
12	Inspection Test Plan	14	NNVA	10; 11	4.2	9.8	10
13	Mobilization	6	VA	10; 12	1.8	4.2	5

Table 12. Comparison of formwork removal step times

No	Work Item (Current)	Time (Hrs)	Work Item (Proposed)	Time (Hrs)	Difference (Hrs)
1	Build stage from pipes	1	Build stage from pipes	1	0
2	Install bottom formwork	1	Install bottom formwork	1	0
3	Install the round bar	0.25	Install the round bar	0.25	0
4	Install fiber rope	0.5	Install fiber rope	0.5	0
5	Install top formwork	1	Install top formwork	1	0
6	Install scaffolding pipes between concrete sections	1	Install scaffolding pipes between concrete sections	1	0
7	Install boards on top of formwork	0.25	Install boards on top of formwork	0.25	0
8	Install gantry / Dismantle top formwork	0.75	Install gantry / Dismantle top formwork	0.75	0
9	Install concrete support scaffolding pipes	1	Install concrete support scaffolding pipes	1	0
10	Dismantle the bottom formwork support pipes	1	Dismantle the bottom formwork support pipes and lower formwork	1	0
11	Dismantle bottom formwork and stage pipes	4	Slide pipes with wheels	1	3
12	Lowering concrete mattress	1	Lowering concrete mattress	1	0
	Total Time	13		10	3

The discussion was used to determine the time required to complete each task and eliminate buffer time in each activity so that optimistic and pessimistic times could be obtained. Optimistic time (fastest time A) is the minimum time for an activity, assuming that everything will go well. The pessimistic time (time with a safety margin S) is the maximum or normal time required for an activity, assuming that the worst-case scenario will occur. These two times will later be used to find the difference between the time and the average estimated time. The following are the results of the discussion and the duration values of the project activities using the cut & paste method with a probability of 30%.

The project activity that experienced a reduction in project duration was the installation and assembly of formwork, rebar, and fiber rope activity, with a duration of 31 days to 21 days, by changing the formwork dismantling method, which initially involved dismantling the bottom of the formwork one by one, to dismantling without dismantling the bottom of the formwork, adding wheels, and then providing a 6 m long C 150 x 75 channel iron for the wheel path so that when it is lowered, it can be immediately shifted and moved for the installation of the next formwork module (Table 12).

A comparison of the time required for the installation and assembly of formwork, rebar, and fiber rope shows a difference of 3 hours for the production of 1 module, and 20 modules according to Fig. 3. The initial process required 31 days, while the proposed method required 21 days. This can be achieved due to two factors: first, the concrete batching plant can only supply concrete until 7:00 PM, and second, with a 10-hour workday, overtime can still be done for the casting process. After the project activity times are obtained, the project activities are then divided into two parts: project activities that are included in the critical path and project activities that are not included in the critical path.

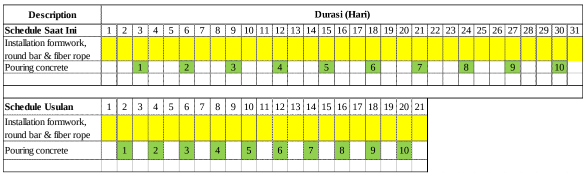

Fig. 3. Schedule for 20 concrete mattress modules

After obtaining the optimistic time for each activity, the next step is to calculate the buffer time. Buffer management is key to managing activities in the critical chain of a project schedule. Buffer time is divided into two buffers, namely the project buffer and the feeding buffer. The project buffer is used to protect work on the critical chain. Meanwhile, a feeding buffer is used to protect critical path activities if there are non-critical path activities that become precedence activities.

Based on the results of the project buffer calculation (Table 13) and the feeding buffer calculation (Table 14), the total buffer time can be determined by adding the project buffer and the feeding buffer. The buffer time result for the Fabrication services of the concrete mattress project is 10 days. The Feeding buffer is located at the intersection leading to the critical chain, which is located after the fabrication formwork activity, the fabrication rebar activity, and the lifting gear activity. The Feeding buffer affects the critical chain when it is 100% used.

From the results of rescheduling using the critical chain project management method, which was then discussed with the project manager, it can be seen that the project can be completed in 79 days, including buffer time. When compared to the existing schedule, scheduling using CCPM will save more time because it is 10 days faster than the existing schedule, which is 89 days. Furthermore, if the buffer time is not used at all, the project duration will be even faster, namely 79 days. From the company's perspective, the acceleration of the project completion duration obtained from rescheduling using the CCPM method will result in a reduction in the costs that the company must incur to pay for labor.

In addition, the optimistic time used in the CCPM method will enable company employees to work more optimally because optimistic time is the assumed time when no problems will occur at all in any company activity. However, the CCPM method still provides a buffer time of 10 days to ensure that the project is completed on time. This buffer time will be used if, during the project, the company encounters problems and needs more time to complete an activity.

The process of using the buffer zone takes into account the use of buffer time in order to control the project being worked on and to plan what solutions or preventive measures to use if the project buffer is fully used. The project buffer is divided into 3 usage zones (Table 15). If the use of the project buffer is in the green zone, the project can be categorized as still safe, or no action is required. For project buffer usage in the yellow zone, the company must develop a plan of preventive measures or solutions so that the project can still run according to plan. The red zone is a condition where the project buffer is almost completely used up or will be completely used up. In this case, the company must immediately implement a plan of preventive measures or solutions so that the project runs according to the initial plan.

Buffer management is used to control buffer time usage. The amount of buffer time consumed will affect what actions the company will take. When buffer time usage is between 7 and 10 days, it will enter the red zone, which means that the project is at risk of being delayed from the schedule, and action must be taken to

Table 13. Project buffer

No	Activity	Pessimistic Duration (S)	Optimistic Duration (A)	$S-A$	$\frac{S-A}{2}$	$\left(\frac{S-A}{2}\right)^2$
1	Kick-Off Meeting	1	1	0	0	0
3	Engineering Verification	7	7	0	0	0
4	Concrete Laboratory, Mix Design, and Trial Mix	14	14	0	0	0
5	Procurement	2	2	0	0	0
7	Fabrication Round Bar	18	18	0	0	0
8	Fabrication Fibber Rope	18	18	0	0	0
9	Installation and Assembly Formwork, round bar, and Fiber rope	31	21	10	5	25
10	Pouring concrete	10	10	0	0	0
12	Inspection Test Plan	14	14	0	0	0
13	Mobilization	6	6	0	0	0
	Total					25

Table 14. Feeding Buffer

No	Activity	Pessimistic Duration (S)	Optimistic Duration (A)	$S-A$	$\frac{S-A}{2}$	$\left(\frac{S-A}{2}\right)^2$
2	Site Preparation	4	4	0	0	0
6	Fabrication formwork	17	17	1	0	0
11	Lifting Gear	20	20	0	0	0
	Total					0

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prevent the project from being delayed. Meanwhile, if buffer time usage is still within the 4-to-7-day interval, it will enter the yellow zone, which means it is safe. In this yellow zone, the company must plan the steps that must be taken so that the buffer is not used up entirely. When buffer time usage is still within the 0 to 4-day interval, it will enter the green zone, which means the project will be completed faster. In this green zone, the company is in a safe and on-schedule position.

Table 15. Project buffer consumption zone indicators

Buffer Consumption	Buffer (days)	Duration	Description
0% - 33%	10	0 – 4	No action required
34% - 66%	10	4 – 7	Plan preventive actions
67% - 100%	10	7 – 10	Implement preventive actions

3.7. *Big Picture Mapping (BPM) Future State*

The results of big picture mapping of the future state show that the production lead time is 79 days (from arrival to product release/delivery) and VA (Value Added) is 58 days (Fig. 4). Meanwhile, NVA and NNVA activities total 42 days. These results show that the process cycle efficiency (PCE) value increased from 65.17% to 73.42%, representing an 8.25% increase in effectiveness. Total value-added time of 108 days with a percentage of 69.23% and a total necessary but non-value-added time of 48 days with a percentage of 30.77%. Meanwhile, activities that are considered value-added have a percentage of 38.46% and necessary but non-value-added activities have a percentage of 61.54%. Value-added time in the current state is 108 days with a percentage of 65.06%, and in the future state, it is 108 days with a percentage of 69.23%. The amount of necessary but non-value-added time in the current state is 58 days with a percentage of 34.94%, and in the future state, it is 48 days with a percentage of 30.77% (Table 16).

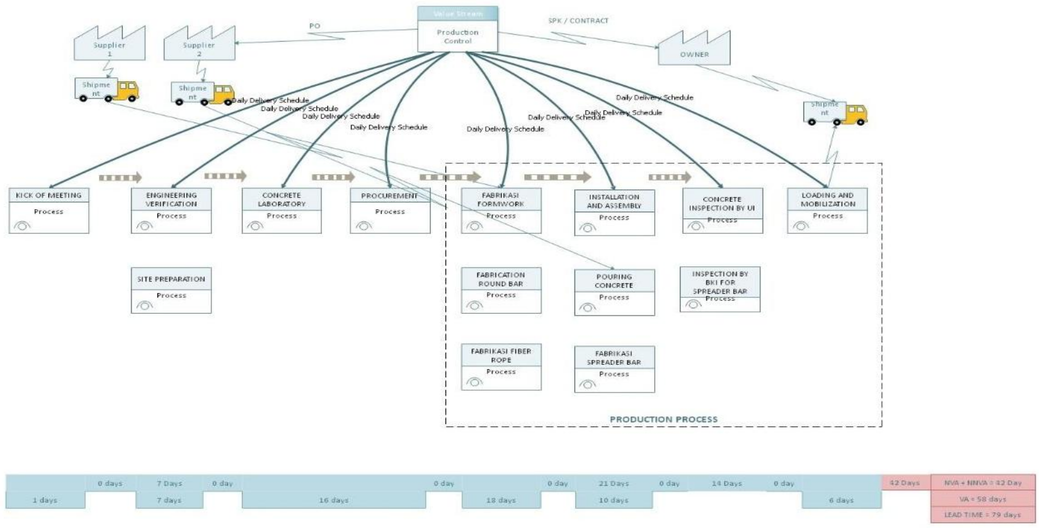

Fig. 4. Big picture mapping of future state activities

Table 16. Current state and future state

No	Activity	Category	Current State - Time (Days)	Current State - Time (%)	Future State - Time (Days)	Future State - Time (%)
1	Kick-Off Meeting	NNVA	58	34.94%	48	30.77%
2	Engineering Verification	NNVA				
3	Concrete Laboratory, Mix Design, and Trial Mix	NNVA				
4	Procurement	NNVA				
5	Fabrication Round Bar	NNVA				
6	Fabrication Fibber Rope	VA	108	65.06%	108	69.23%
7	Installation and Assembly Formwork, round bar, and Fiber rope	VA				
8	Pouring concrete	VA				
9	Inspection Test Plan	VA				
10	Mobilization	VA				
11	Kick-Off Meeting	VA				
12	Engineering Verification	VA				
13	Concrete Laboratory, Mix Design, and Trial Mix	VA				

4. CONCLUSION

Data processing results revealed several types of waste occurring in the concrete mattress fabrication services project. The critical types of waste were motion waste, waiting waste, and defect waste. Analysis of the root causes of waste revealed that they were the formwork dismantling method, lack of worker expertise, lack of vibrator machine maintenance, and poorly managed supplier databases. Steps to minimize waste by reducing critical waste, the formwork dismantling method falls into the extreme category. The first alternative is to change the formwork dismantling process using wheeled tools and C 150x75 channels as rails, which will cut the time needed to dismantle and reassemble the formwork. The second alternative is to provide buffer time using the Critical Chain Project Management method. Steps to minimize delays in the Fabrication service of the concrete mattress project are to minimize the use of buffers, so that the project can be completed faster than 89 days. If the buffer time is used between 7-10 days, then the company must implement the planned actions so that the project does not experience delays. Further research is expected to use case studies that consider overall risk identification and costs.

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