

## Article

# Cost Based Value Stream Mapping as a Sustainable Construction Tool for Underground Pipeline Construction Projects

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**Abstract:** This paper deals with application of Value Stream Mapping (VSM) as a sustainable construction tool on a real construction project of installation of underground pipelines. VSM was adapted to reduce the high percentage of non-value-added activities and time wastes during each construction stage and the paper searched for an effective way to consider the cost for studied construction of underground pipeline. This paper is unique in its way that it adopts cost implementation of VSM to improve the productivity in underground pipeline projects. The data was observed and collected from site during construction, indicating the cycle time, value added and non-value added of each construction stage. The current state was built based on these details. This was an eye-opening exercise and a process management tool as a trigger for improvement. After the current state assessment, a future state is attempted by Value Stream Mapping tool balancing the resources using a Line of Balance (LOB) technique. Moreover, a sustainable cost estimation model was developed during current state and future state to calculate the cost of underground pipeline construction. The result shows a cost reduction of 20.8% between current and future states. This reflects the importance of the cost based Value Stream Mapping in construction as a sustainable measurement tool. This new tool could be utilized in construction industry to add the sustainability and effective cost management.

**Keywords:** Value Stream Mapping (VSM); Line of Balance (LOB); sustainable construction; underground pipeline project

## 1. Introduction

The construction industry is increasingly moving towards the adoption of sustainable strategies and increased efficiency targets [1]. Value Stream Mapping (VSM) is a new phrase that originates from Toyota's material and information flow diagrams and was designed to help Toyota's suppliers learn the Toyota Production System [2]. VSM is a lean management system to assess the current state and a designed future state for the series of activities from beginning to hand-over. VSM is not just only a tool and limited to identify wastes in a system, but it is used to analyze and assist in designing processes, tracing material flow, and documenting information flow of a given product family. VSM adapts symbols to represent a clear and visual process from the customer's requirements to the final accomplishment.

Despite the efforts for sustainability studies in building and infrastructure construction, the sustainability issues in industrial construction remain understudied [3]. The application of VSM in real construction industry has not received enough attention by researchers due to the difficulty in implementation of VSM in a real construction activity. In this paper, construction of an underground pipeline project was practically assessed by VSM as a sustainable construction method. In this context, cost based Value Stream Mapping is developed as a measurement tool to build an optimized future

state with less cost. Cost based Value Stream Mapping considers the customer value as the guide which basically eliminates the time wastes to get more production with high quality. Thus, the integration of VSM and cost methods were used together to develop a systematic framework. The contribution of this paper to existing knowledge can be stated as introduction of a cost based VSM methodology in underground pipeline projects. The cost based VSM technique was utilized on a real case study to evaluate the difference between traditional cost and VSM improved cost. This paper attempts to identify, develop and apply a concept of cost based VSM in construction sector, which can serve as a new way forward for future cost estimation.

## 2. Literature Review

### 2.1. Value Stream Mapping Principle

Value Stream Mapping (VSM) technique was introduced in second half of twentieth century by Toyota Motor Company which became one of the important lean management methods. Value Stream Mapping (VSM) has become a popular method for lean thinking and implementation in recent years [4]. Basically, it is graphically presentation production processes starting by using a raw material as an input to deliver the customer's product as an output. Martin et al. [5] defined VSM as "the sequence of activities an organization undertakes to deliver on a customer request".

The VSM is strictly divided into three types of operations that are undertaken: (1) Non-value adding; (2) Necessary but non-value adding; and (3) Value-adding. The first is pure waste with unnecessary actions that should be completely eliminated. The second one involves actions that are necessary but might be wasteful. VSM was not limited only to identifying waste in a system, but could also be used to analyze and assist in designing processes, tracing material flow, and documenting information flow of a given product or product family [2]. Wastes originates mostly from schedule deviation and can be generated in stationary or nonstationary productions, Figure 1 illustrates the type of wastes and provides example in each case.

VSM uses symbols to represent a clear and visual process from the customer's requirement to the final accomplishment. Drawing a value stream map is the result of implementing a VSM tool.

In summary, VSM provides a visual, full-cycle macro view of how work progresses from a customer request to the final fulfilment of that request. The mapping process deepens the understanding of work systems that deliver value to customers and reflect the work flow from a customer's perspective. As a result, the process of Value Stream Mapping provides effective ways to establish strategic directions for better decision making and work design.

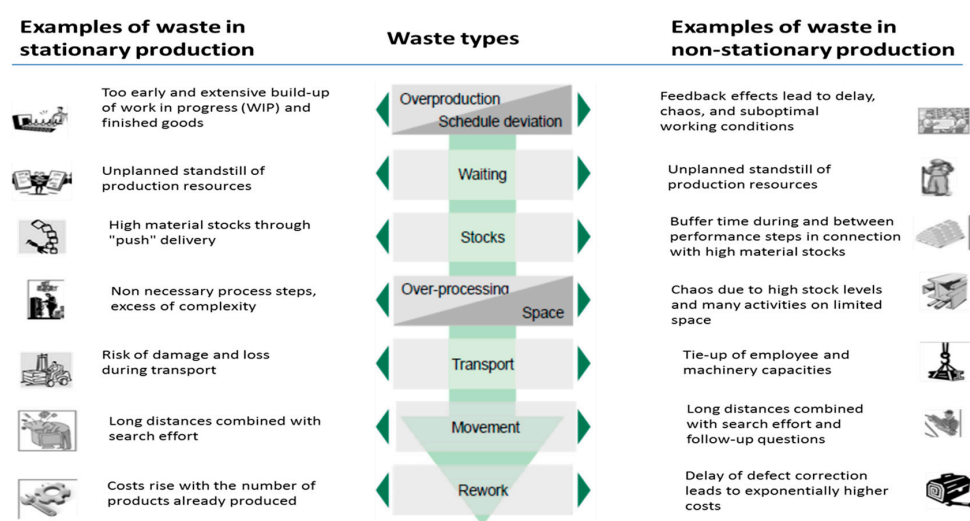


Figure 1. Classification of wastes in stationary and non-stationary productions.

Schmidtke et al. [6] developed an enhanced VSM method, which utilizes discrete event simulation (DES). The method featured a feasibility and trade-off analysis which is incorporated into the VSM procedure. Sabaghi et al. [7] focused on three lean manufacturing techniques, which are Kanban production system, setup time reduction, and total productive maintenance (TPM) in a plastic fabrication industry. Suarez-Barraza et al. [8] describe the implementation of a tool called Supply Chain Value Stream Mapping (SCVSM) in order to thoroughly understand competitive priorities of volume and delivery (On-time Delivery (OTD)) for any supply chain in organizations. Throughout the case study by Yuvamitra et al. [9], implementing changes in both the information flow system and the material flow system would save an estimated 75% for the manufacturing time of the rope.

## 2.2. Value Stream Mapping and Sustainability in Construction

Value Stream Mapping has been used in many industries. Tyagi et al. [10] used Value Stream Mapping (VSM) to explore the wastes, inefficiencies, non-valued added steps in a single, definable process out of complete product development process. Wang et al. [11] proposed a supplier selection framework tailored to effective information integration for supply chain management. Jeong et al. [12] examined critical factors affecting productivity at the operational level, and then forecast the productivity dynamics. By integrating BIM with construction operation simulations, they were able to develop reliable construction plans that adapted to project changes. Lee et al. [13] developed a hybrid estimation model to predict the quantity and cost of waste in the early stage of construction. Jia et al. [14] proposed a Therblig-embedded Value Stream Mapping (TVSM) method to improve the energy wastes.

Construction projects are complex systems that inherently contain complex interface problems [15]. In spite of being successfully applied into different industries, the application of Value Stream Mapping in construction is limited. There are only few studies on VSM in construction, and they refer more to construction supplies rather than to the process itself. Pasqualini et al. [16] described the modified application of VSM in a Brazilian construction company; some adaptations were made in each stage of VSM. Another example is a case study of housing construction. Yu et al. [17] worked on a case study of the standard wood platform-frame structure, the case of 400 houses construction was regarded as repetitive works. These two cases demonstrate that VSM is a tool used to identify the sources of environmental and production waste, quantify them, and suggest reduction strategies.

Shou et al. [18] presented a literature review of the Critical Success Factors in the implementation of VSM across five different sectors: manufacturing, healthcare, construction, product development, and service. The review covers the peer-reviewed journal articles on VSM in Scopus from 1999 to 2015. The findings of this study provide a good basis for industry practitioners to effectively implement VSM in construction industry.

Pasqualini et al. [19] presented a methodology for modeling multi-product manufacturing systems with dynamic material, energy and information flows with the aim to generate economic and environmental value stream maps (E<sup>2</sup>VSM). The proposed methodology is validated with an industrial case not in construction industries.

Dinesh et al. [20] described in a case study a production of a heavy-duty electrical transformer with some approximations and simplifications with a VSM application.

Rosenbaum et al. [21] utilized a case study of the VSM application as a green-lean approach in the construction of a hospital in order to improve its environmental and production performance during the structural concrete work stage. The paper presented the implementation process of the value stream for future state by aggregate tools to enhance productivity improvement.

Mok et al. [22] showed that VSM and simulation tools when combined together form a strong integration tool for improving the work productivity. This paper deals and covers complex environments of projects such as introduction of pipe spools (pipe with elbows or tees or flanges, etc.), which was not covered in Reference [22]. Moreover, this paper differs from this study by evaluating the effectiveness of integration of VSM, Line of Balance (LOB) and cost based VSM as a

tool to improve the value added. After the assessment of the current state, the future state of VSM is attempted by using LOB for resource levelling which has a major contribution in the cost reduction. The application of LOB technique and cost based VSM are totally new contribution to the literature in these types of projects. In this paper, the application of VSM tools in the complex environment conclude that the micro-concepts, takt time, supermarket to facilitate pull, continuous flow and space maker was properly utilized to facilitate VSM applications, one often requires adjustments, averaging and approximation in terms data collection, linearity in flow and timings. These new tools are contribution to current body of knowledge. This paper developed a better understanding of VSM and how it can be modified, with LOB method and how the manpower aspect is considered in this research. In the contrary, the manpower aspect was not considered in Reference [22]. Moreover, it introduced a developed concept to calculate the cost of Value Stream Mapping on a weekly basis. This technique can be utilized to understand the construction progress status and the future expectation. Moreover, it can be used to calculate the cost of similar projects for tendering purposes.

The above thorough literature in construction shows the importance of implementation of VSM and sustainability in construction as a lean management tool to reduce the time wastes and increase the value added in the processes. As currently understood, VSM needs to be linked with the cost to a better optimal production rate. This study will focus on this perspective.

### *2.3. Line of Balance in Lean Construction*

The literature reviewed papers emphasize on VSM philosophy, identifying activities that develop value and in line with concept of reduction of time waste. Therefore, LOB is studied in order to identify its potential relationship as a resource levelling tool to the principles of VSM in construction. According to Pinheiro et al. (2009), repeating units of work might cause learning effects, what leads to the reduction in activities duration. The smaller the repeating unit, the greater the learning effect, what reduces also global lead time.

This study utilized LOB tool as a planning device that gives support to the VSM concept by proper utilizing the resources to calculate the cost based VSM.

## **3. Methodology**

There is limited research that utilized a VSM to calculate the cost for current and future states in the construction industry. Such studies were concentrated and focused on manufacturing domain only. In this study, the concept of cost reduction was addressed in construction by using a Value Stream Mapping. More specifically, the Value Stream Mapping was applied on a real underground pipeline project. The construction processes were optimized based on the cost according to Value Stream Mapping technique. This was achieved by comparing a cost of current state with a cost of future state, which attempts to evaluate the objective of Value Stream Mapping in construction. The same can be set as a model for proper utilization and estimation to similar repetitive projects in future. Cost items include labor cost, materials cost, production support cost, equipment cost, operation support cost, facilities and maintenance cost, all other value stream cost, as shown in Figure 2.

The very first step in this study is to form a comprehensive current state for the construction process. This is a vital step as it lays the ground for a full understanding the processes in construction and find out the time wastes. By the Value Stream Mapping concept, the wastes were measured and identified in the current state. Then, the future state was formulated accordingly to improve the productivity and reduce the time wastes. Work plan and required manpower was set according to feedback from current state to optimize the process and ensure wastes are minimized in combination with Line of Balance technique (LOB).

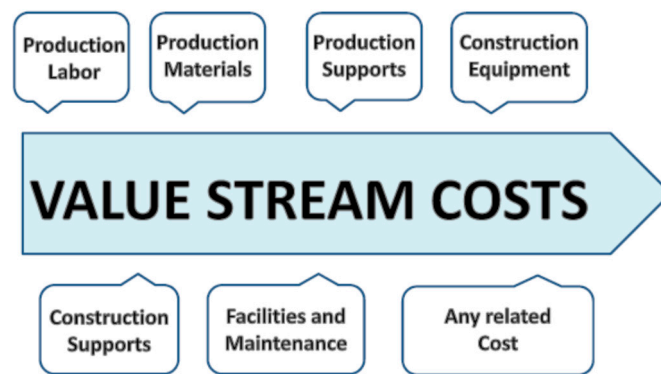


Figure 2. The elements for cost based Value Stream Mapping (VSM).

The basic concepts of LOB have been applied in the construction industry as a resource driven scheduling method. Line of Balance (LOB) is a method of showing the repetitive work that may exist in a project as a single line on a graph. Recently LOB has been associated with lean construction applications, especially as a tool for tactical planning of works. In this study, LOB will be introduced along with the VSM to reduce the lead time. The smaller the repeating unit, the greater the learning effect, what reduces also global lead time as shown in Figure 3.

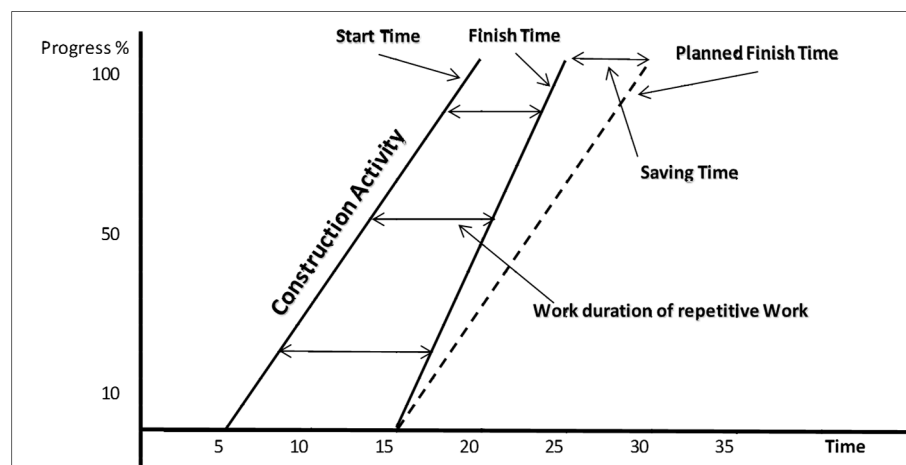
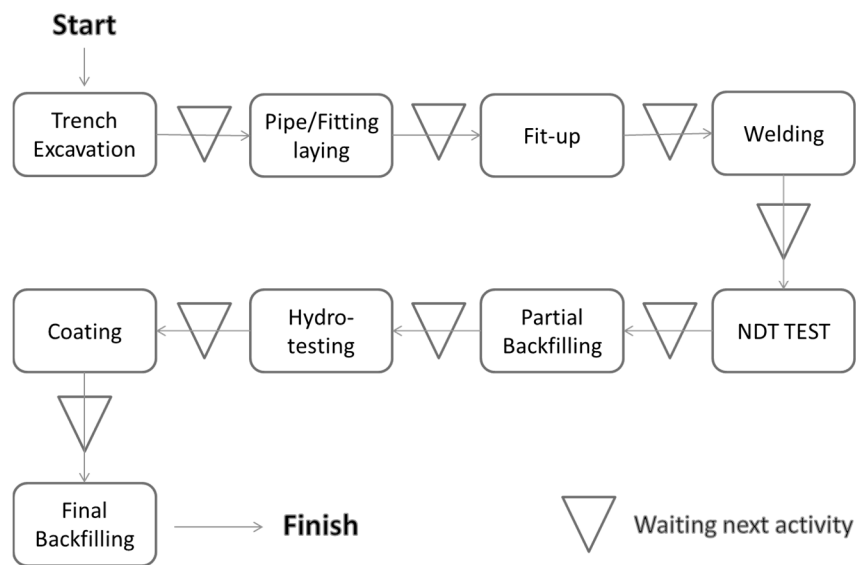


Figure 3. Improvement of the total lead time for repetitive work.

The cost based of Value Stream Mapping is calculated weekly and it takes into account of all costs related to value stream. The cost calculation was done for current and future states and then a comparison between them has been evaluated for estimation and bidding purpose for similar future projects.

#### 4. Data Characteristics

In this study, an underground pipeline project was selected to apply VSM. The main purpose of selection is the effectiveness in data collection and repetitiveness of the activities. As per project contract, the scope of work was construction of a pipeline (36-inch diameter) with a network of 36.5 km. The first step in the Value Stream Mapping technique is to develop a process flow diagram to provide a clear picture about every stage for the construction of underground pipeline. Figure 4 shows the work flow diagram for the Value Stream Mapping.



**Figure 4.** Work flow diagram.

Monitoring and recording with stop-watch was conducted to record the actual cycle time for each construction stage accurately as presented in the below Table 1.

**Table 1.** Cycle time for each construction stage.

Construction Activity	Cycle Time (Minutes)
Trench Excavation	193.0
Laying Pipes & Fittings	130.0
Fit-up	128.0
Welding	600.0
NDT Test	320.0
Partial Backfilling	48.0
Hydro-testing	181.0
Painting	179.0
Final Backfilling	601.0

With collected data, the Value Stream Mapping for construction of six pipes can be built based on VSM basic concept. The Value Stream Mapping is the most efficient and functional tool which furnishes the current state of the construction stages to find out the wastes. It envisions the value-added time (VAT) and Non-value-added time (NVAT) for each construction stage and introduces the actual stage for the entire process to evaluate the current total lead time. From the collected data, the following is the current state of construction of pipeline as shown in Figure 5. Meaning of Samples and Icons for current and future states of Value Stream Mapping is available in Appendix A.



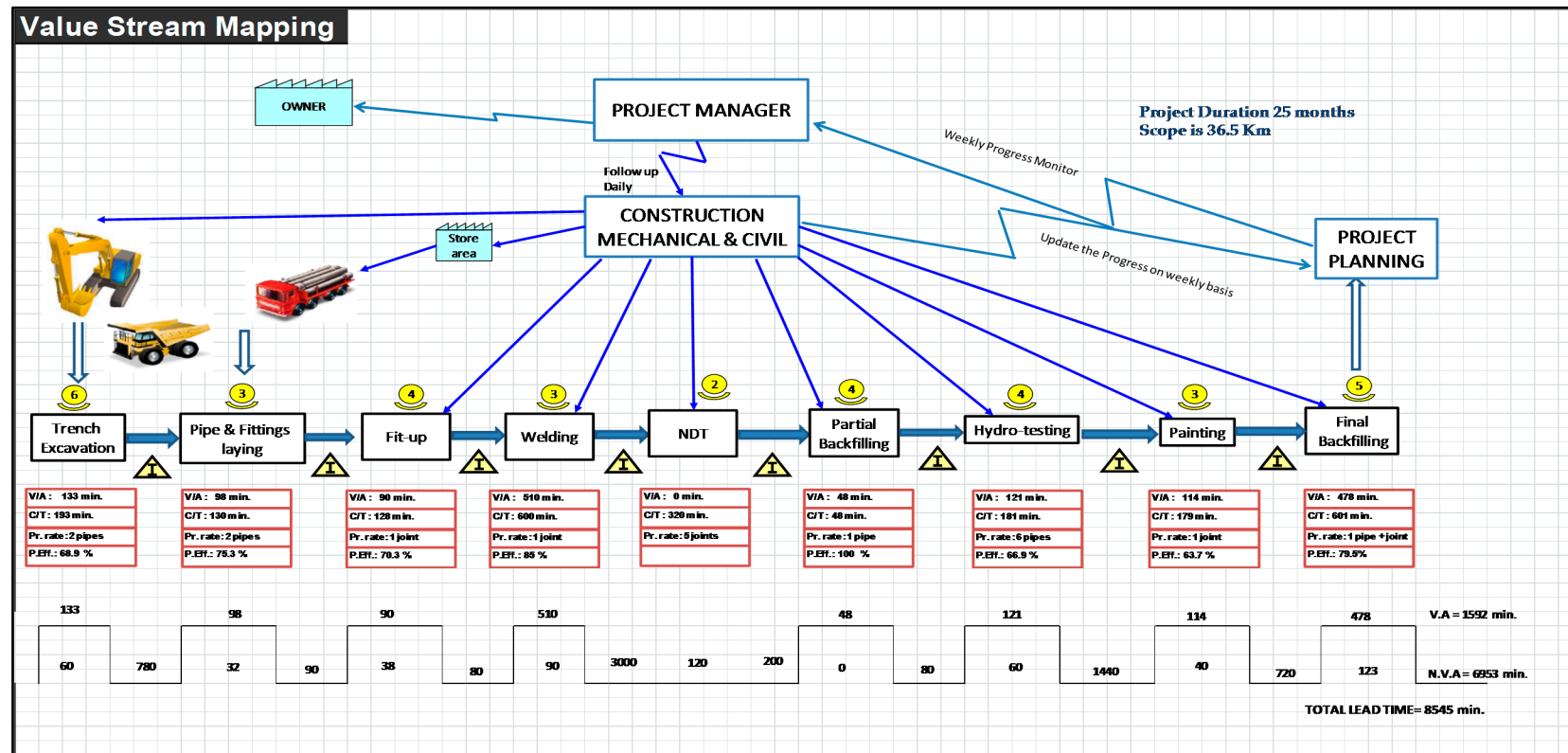


Figure 5. Current state of VSM for construction of underground pipeline.

## 5. Data Analysis for Current State of VSM

The duration was observed for each individual activity. The actual time spent during physical and productive construction was recorded as VAT and the time consumed during non-productive construction such as waiting, idle, rest and standby times were recorded as NVAT.

The percentage of VAT to the total lead time was 18.6%. The waste percentage is quite high compared to the total lead time in the construction process. Therefore, the total lead time has to be reduced by enhancing the progress and eliminating the non-value-added activity.

The customer would specify the quantity of the required products on daily, weekly, monthly or yearly basis based on the placed purchase order. The takt time is defined as the rate at which a pipe joint must be completed to complete the construction of underground pipeline to satisfy the client requirements.

This difference implied in a new form of calculating takt time for construction, obtained by means of the division of the effectively available time for each stage by amount of joint to be executed. As result, takt time of the construction will indicate the time in which one pipe joint should be completed, stipulated in the contract planning base line.

For aforementioned case study at the beginning, the project scope is to install 36,500 m of underground pipeline; the pipe size is 36-inch in diameter and shall be completed within 25 months. Based on the above information and as contingency plan, an internal schedule has been built and the project shall be completed with 23 months consequently. According to project scope 3343 joints must to be completed.

$$\text{Targeted productivity rate} = \frac{\text{Number of joints}}{\text{Available time}}$$

$$\text{Available time} = 23 \text{ months} \times 26 \text{ days} = 598 \text{ days.}$$

$$\text{Number of joints} = 3343$$

$$\text{Targeted productivity rate} = \frac{3343}{598} = 5.6 \text{ joint/day.}$$

As a result, the takt time in construction is defined by a required time to produce one joint as it is stipulated in the contract.

$$\text{Takt time} = \frac{\text{Available working time per day}}{\text{productivity rate per day}} = \frac{600 \text{ min}}{5.6} = 107 \text{ min.}$$

(This is the takt time required to complete installation of one pipe and one joint.)

The cycle time for all entire construction activities is higher than the takt time. The welding and final backfilling processes are the bottleneck of the entire process; this means there will be waiting time to complete these activities and expecting idle manpower. Thus, the construction activities have to be synchronized to achieve the rhythm of takt time and complete within contract duration.

### 5.1. Cost Based Current State of VSM

The value stream cost is basically calculated weekly and takes into account of all costs in the VSM. As mentioned previously all costs related to VSM is considered as a direct cost. Any cost outside the Value Stream Mapping is not included in the costing of Value Stream Mapping. Weekly cost of VSM is listed in detail in Table 2. The total cost is \$19,477 which will be compared with a cost of future state Value Stream Mapping later to investigate and evaluate the difference between these two costs.



**Table 2.** Cost of current state activities.

Current State of VSM	Employee Cost (\$)	Production Support Cost (\$)	Maintenance Cost (\$)	Machine/Equipment Cost (\$)	Other Costs (\$)	Total Cost (\$)
Trench Excavation	1306	250	550	1096		3202
Pipe & fittings laying	583	286	389	603		1861
Fit-up	755	250				1005
Welding	617	500	150	274	300	1841
NDT		20		350		370
Partial Backfilling	1062		150	822		2034
Hydro-testing	754	145	130	250		1279
Painting	617	250	95			962
Final Backfilling	822	250	255	1096		2423
	4500 (Construction Managers and Site Engineers)					4500
<i>Total</i>						19,477

Note: Employee cost: is the basic salary including the employee benefit. Production support cost: Expenses not directly associated with construction activities such as design, engineering, and procurement. Maintenance cost: Cost to keep equipment or machine in good working condition. Machine/Equipment cost: In this research, rental and operating cost.

## 5.2. Suggested Improvement and Future State of VSM

The following suggested improvements were developed according to the construction status in guidance with the implementation of the modified basic concept of Value Stream Mapping.

### (a) Pull system and synchronize first-in/first-out flow:

Trench excavation, partial and final backfilling: the process cycle time for each activity is higher than takt time. The required improvement is to reduce the non-value added especially the waiting time which is required to prepare the trench, bedding and inspection prior to place and laying the pipes. The excavation is the first construction activity; thus, it would be better to assign an excavation team to start the excavation activity one hour in advance which would provide enough time for the next activity to start earlier. Moreover, it was proposed to introduce a continuous flow and develop an open work front by eliminating the partial backfilling activity. The agreement between the main contractor and consultant was developed to proceed with painting and coating after completion of NDT (Non-destructive test). Then, the pipeline will be backfilled finally to be ready for final testing. In Value Stream Mapping, it is called first-in/first-out or pull system, where a downstream pulls the upstream activity to improve the work flow and improve the utilization of manpower and equipment. Thus, 24 hours was given to backfilling team to complete the final backfilling after completion of five joints. The application of continuous flow, the non-value-added time for trench excavation, partial backfilling and final backfilling has been reduced.

### (b) Combined and restructured the work activities (fit-up and welding activities):

The time required to complete the installation of one joint is 107 min. Welding activity has high cycle time, therefore and in coordination with the engineering team, a technique called Weld Map Drawing was initiated. Basically, welding map is an isometric drawing that shows the location for all pipe joints in the project, as shown in Figure 6.

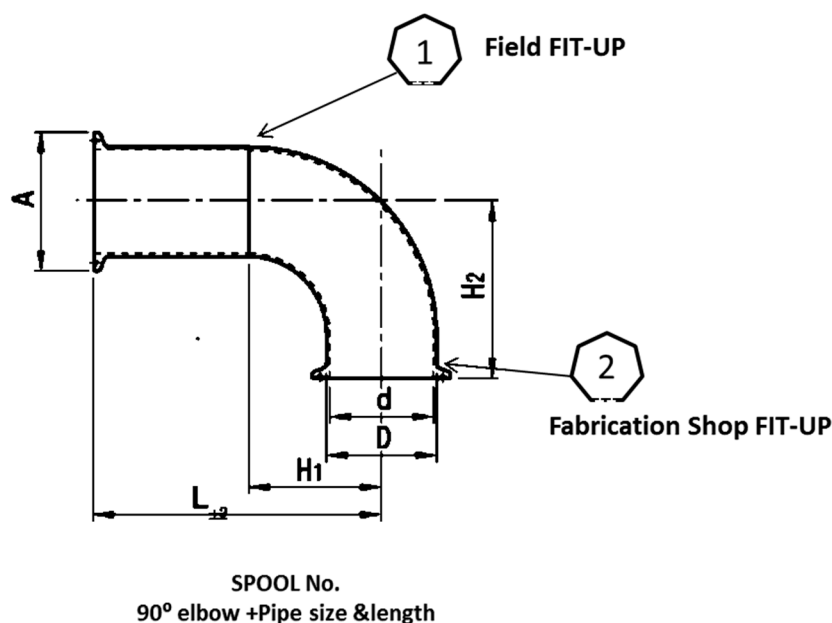


Figure 6. Sample of weld map drawing.

Normally, the field engineering section in coordination with construction field would study and investigate thoroughly in detail each joint and specify the joint status with respect to field weld or manufacturer joint weld named as spools. After finalizing the list, the spools would be submitted by

construction team to manufacturer, this would allow construction and spool manufacturer to track and expedite the spool fabrication till completion date. By weld map drawing and spool concept, the welding cycle and lead times will be reduced accordingly. To speed up the welding process, the construction team may ask the engineering to generate a list of tack welding spools.

In this study, the joints that can be fabricated in the shop by manufacturer are 1171 joints and the construction team suggested to reduce the idle time of the workers by merging the group of fit-up and welding teams for identical tasks. The pipefitters were subject to tack welding training for two weeks period which enhanced the productivity of welding process. The implication for the above strategy was significant. The observation for welding activity cycle time is reduced and total lead time is reduced as well.

(c) Production leveling by pacemaker/supermarket:

Welding and NDT activities: The concept of Supermarket Pull System between welding process and NDT process was introduced. Basically, the supermarket pull system is a controlled inventory of joints that is subject to testing schedule in due course according to site situation. Therefore, the joints were accumulated to perform NDT test in one shot. Moreover, the NDT was scheduled to be during the night to perform more tests without any interruption. According to project baseline.

Schedule, the takt time was scheduled to produce 5 joints per day to meet the project completion date. The completion date was scheduled two months ahead, as a safety factor. The proposal was introduced to prepare 5 joints for test which facilitate an open front for other activities and optimize the resources effectively.

The concept of pacemaker loop encompasses the flow of information and material between the mainly construction and testing. The downstream loop is impacted by the upstream loop and this can't be done without proper scheduling and continuous development.

(d) Work restructuring to improve the construction reliability:

Hydro-testing was scheduled after completing the NDT test, painting and final backfilling, which was in coordination and approval of project resident engineer. To ensure a proper stability and anchorage for the network integrity, the final backfilling has taken place prior to proceed with hydro-test. This was suggested to apply the concept of Supermarket Pull system and to ensure a continuous flow. This can be achieved by batch of Kanban (It is a Japanese term that gives authorization and instructions for the production or withdrawal conveyance of items in a pull system) by preparing a minimum of 5 completed welded joints for NDT test and build a ready pipeline for hydro-test according to site condition. By this improvement hydro-testing activity were improved significantly.

(e) Painting:

The cycle time of the painting process is higher than takt time, thus, the wastes and waiting time has to be minimized. Due to the super market concept which was introduced and developed between welding and NDT activities, the continuous flow is generated to catch-up the quantity of joints generated after hydro-testing.

(f) Manpower leveling and LOB (Line of Balance):

Integration of LOB with VSM played a vital role to level the required manpower. In this study, the resource leveling was achieved by identifying the number of crews required to complete the project on the time. The study used velocity rating diagram to find required resources for each stage so each work stage can be done by synchronized crew and continue without interruption. According to LOB technique, the following information was applied:

- Vertical axis plots cumulative progress of number of joints completed in the project. Horizontal axis plots time and sloping lines represent rate of production i.e., number of joints per day.

- To complete the project and minimize the waste and lead time, the crews are distributed as following:
  - (1) Two crews for excavation and final backfilling. Each crew consists three civil workers under one supervisor.
  - (2) One crew for pipes and fittings laying (three pipe fitters)
  - (3) One crew for fit-up and welding (four welders and three helpers)
  - (4) One crew for NDT testing (two NDT technicians)
  - (5) One crew for painting (three painters)
  - (6) One crew for hydro-testing (four mechanical/pipe fitters).

The repetitive activities are distributed uniformly to ensure a proper utilization of manpower and tools, as in Figure 7.

### 5.3. Proposed Future State of VSM

The previously mentioned improvements were implemented in the current state to achieve the future state as illustrated below in the Figure 8.

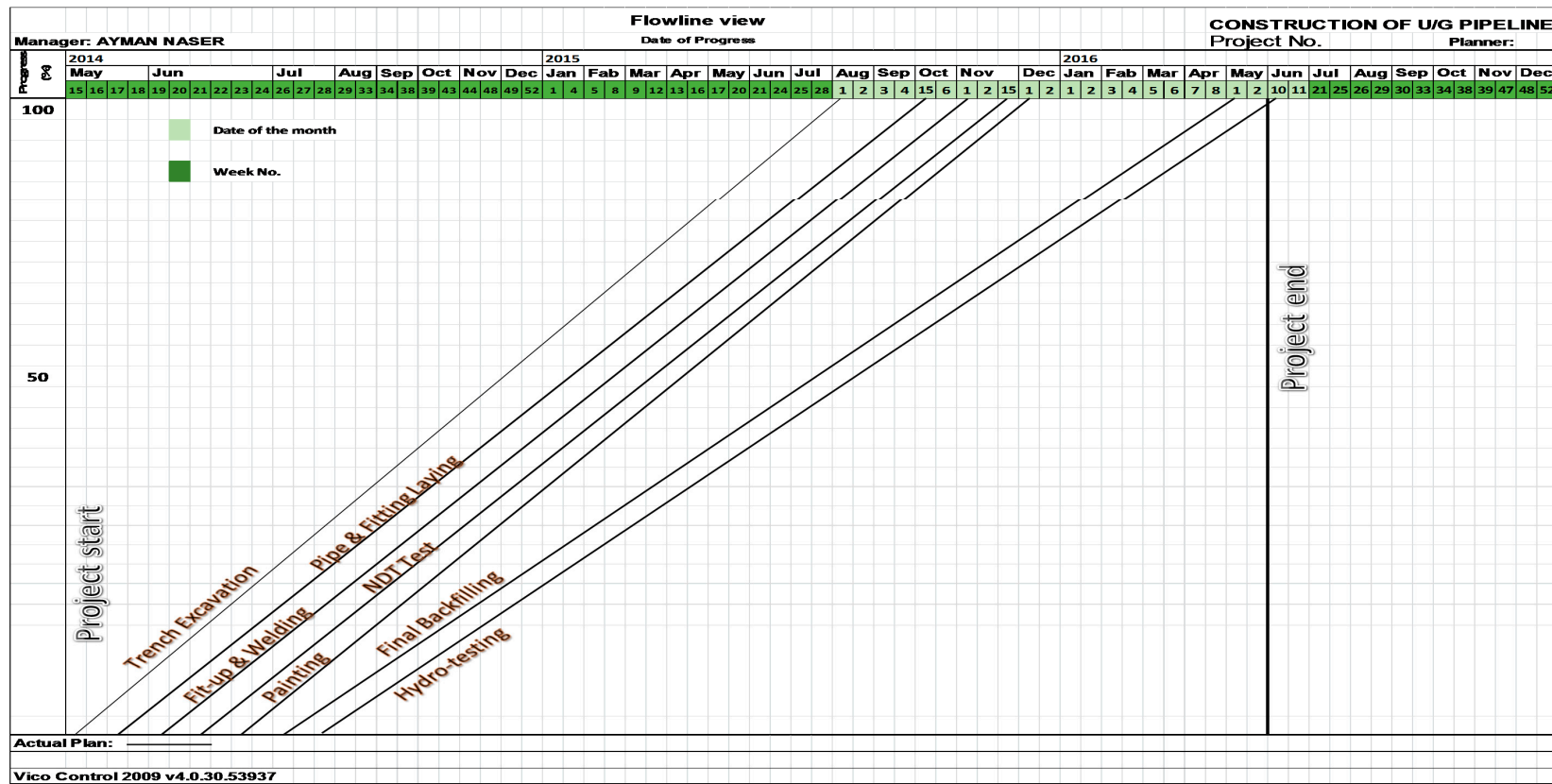
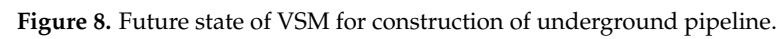


Figure 7. Line of Balance (LOB) for resource levelling.





Future state of VSM shows a significant improvement in the construction process. It has been observed with a reduction of total lead time, reduction in the time wastes (NVA) and increase in value added time (VA). Table 3 shows the achieved improvements:

- The lead time was calculated in current state 8545 min based on construction of one joint. While, the total lead time in the future state is 5922 min. There is an improvement of 30.7%.
- The value-added time in current state is 1592 min, and it is improved by 43.3% as 903 min.
- With application of VSM, the non-value-added time is reduced by 27.8%. The NVA was reduced from 5019 min to 6953 min.
- The comparison of production capacity for current and future states is based on one joint and one pipe for current and future states of VSM.

**Table 3.** Production capacity comparison between current and future states of VSM.

Construction Activity	Current State	Future State	Improvement
Lead Time (min)	8545	5922	30.7%
Value Added (min)	1592	903	43.3%
Non-Value added (min)	6953	5019	27.8%
Production capacity	1 joint/1 pipe	1 joint/1 pipe	

As a result, future state map has to be validated on continuous improvement basis. Takt time for the construction can be calculated based on the customer's requirement and according to signed contract between the parties. Thus, each process possesses different takt time to be executed and calculated accordingly. Therefore, takt time shall be developed by establishing a pull system, introduce a levelling system, and establish a pacemaker loop for the future state of VSM. The takt time for supply and pacemaker loops was developed to meet the contract completion date. The time for supply loop is 2307 min and the required time to complete the pacemaker loop is 4700 min with a control inventory of supermarket time of 3000 min. The construction capacity was adjusted to construct five joints and six pipes. Thus, the takt time for each process loop was balanced to meet the project completion date accordingly.

#### 5.4. Cost Based Future State of VSM

Cost of future state was calculated to evaluate the importance of total cost reduction by Value Stream Mapping. After suggestion improvements and the formulation of future state of Value Stream Mapping, the cost has been calculated and summarized in Table 4 of the weekly period as previously implemented in the current state.

In comparison between the cost based for current and future states of Value Stream Mapping, the reduction in cost is 20.8%. It shows the importance of utilizing the Value Stream Mapping in construction as a management tool. Moreover, this technique provides an accurate cost calculation method that can be used for tendering purposes.

**Table 4.** Cost of Future state activities.

Future State of VSM	Employee Cost (\$)	Production Support Cost (\$)	Maintenance Cost (\$)	Machine/ Equipment Cost (\$)	Other Costs (\$)	Total Cost (\$)
Trench Excavation	1424.7	250	550	310.5		2535.2
Pipe & fittings laying	602.7	286	389	125.4		1403.1
Fit-up						
Welding	1095.9	500	150	82.2	300	2128.1
NDT		20		350		370
Partial Backfilling						
Hydro-testing	754	145	130	250		1279
Painting	617	250	95			962
Final Backfilling	1424.7	250	255	310.5		2240.2
	4500					
	(Construction Managers and Site Engineers)					4500
<i>Total</i>						15,417.6

## 6. Discussion of Results

The objective of this paper is to enhance and develop the utilization of VSM as a lean management tool in construction industry and emphasis the VSM benefits by adapting of a cost based VSM.

The paper deals with the possibility of implementing the design method of Value Stream Mapping (VSM) supported by Line of Balance (LOB) on a construction project focused on the installation of underground pipelines with a perspective of cost. More specifically, the cost implementation of the proposed method enables to reduce the project by comparing its current and future costs and improving its productivity.

Alvandi et al. [19] validated an industrial manufacturing case study to present a methodology for modeling an environmental Value Stream Maps without consideration of cost and resource levelling.

On other hand, Dinesh et al. [20] utilized a manufacturing plant with some approximations and simplifications in VSM application. While in this paper, construction environments are systematically studied for the manpower and cost with Value Stream Mapping as a lean tool.

The research by Jeong et al. [12] presented a Building Information Modeling (BIM)-integrated simulation framework for predicting productivity dynamics at the construction planning phase only. While in this paper, the concept is applicable for all phases of planning, bidding and execution.

Mok et al. [22] represent a flow diagram to depict the VSM tools. While in this paper, the application of VSM tools in the complex environment such as the mico-concepts, takt time, supermarket to facilitate pull, continuous flow and spacemaker were properly utilized to facilitate VSM applications. In addition, it evaluates the effectiveness for integration of VSM, LOB and cost as a tool to improve the value added and reduce the time wastes in construction activities.

The proposed method in this research introduces a significant contribution deals with resource levelling and cost estimation can be utilized in the entire project phases. This research has focused on developing a stable production flow rather than eliminating individual waste. VSM, a powerful lean construction tool, was used to analyze the construction process and restructure the production system.

Several papers described the achieving constant process improvement in manufacturing/plant production is by Value Stream Mapping only. By being the part of construction industry with the ability to bring in cost and productivity advantages, a Value Stream Mapping stands as a more attractive alternative when compared with the other conventional management tools. To capitalize on such benefits, the followings were observed as remarkable improvements:

After analysing the application of Value Stream Mapping in construction industry and demonstrate the physical application by using a real case study, the total VAT was improved by 43.3% with respect to cycle time While the NVAT was reduced by 27.8%.

After introduction of the LOB with VSM, the total lead time was reduced by 30.7% and required manpower was reduced by 12.5%. The major contribution of integration of LOB tool with VSM was to optimize the resources utilization and reduce the total lead time.

The cost is reduced by 20.8% in comparison between two VSM states.

## 7. Conclusions and Recommendations

This paper developed a better understanding of VSM and how it can be modified, with LOB to be applied in the construction industry. Moreover, it is introduced a developed concept to calculate the cost of Value Stream Mapping on a weekly basis. This technique can be utilized to understand the construction progress status and the future expectation. Moreover, it can be used to calculate the cost of similar projects for tendering purposes.

This paper attempts to address the application of Value Stream Mapping to a real-life problem of an underground pipeline project. It analyzed the improvement of VAT and reduction of NVAT compared with the cycle time. It studied the reduction opportunity in total lead time. LOB tool with VSM as a new tool provided a powerful attempt for proper resources utilization and monitoring to improve the VAT and decrease the total lead time.

Although several papers addressed using VSM as a lean tool to reduce waste and add value during the construction process, no detailed and unified VSM instructions exist concerning how to implement it in construction to evaluate the improvements and calculate the cost reduction. This paper tried to cover this gap. Suggested improvements will result in achieving the production and capacity demand to meet project completion deadline. Future research can be extended and focused further on the following: Applying Value Stream Mapping for other repetitive and non-repetitive construction activities; integrating and combining VSM with other tactics and lean management tools to improve the benefits of Value Stream Mapping in the construction industry; incorporating and evaluating the cost based VSM for bidding and estimation purpose; introduction of a simulation based VSM software that can be used to study the construction time and cost in advance for future construction.

This study has some limitations as it deals with a specific construction company and different environments, such as—but not limited to—a project, owner, project specifications, main contractor, operations and other environment-based constraints.

Another limitation is the process of integration the cost-based of Value Stream Mapping concept in the budget and estimation calculation as a vital tool in the construction companies for bidding purpose. This can be developed for future studies.

Moreover, no simulation modeling was used to develop different scenario requirements to compare current state with different scenarios for future state and optimize the cost. This can be expanded for future research.

To extend the body of knowledge, the paper findings can be attempted for other areas such as construction of high-rise building. Similarly, the construction challenges for green building can also attended under the umbrella of Value Stream Mapping.

**Author Contributions:** Both authors were involved in the development of this paper. Murat Gunduz and Ayman Fahmi Naser organized the paper together. Both authors worked together during the development of graduate study outputs of Ayman Fahmi Naser into this paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

Table A1. CValue Stream Mapping Symbols &amp; Icons.

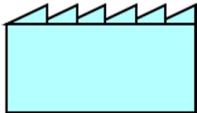

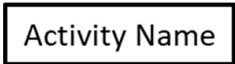
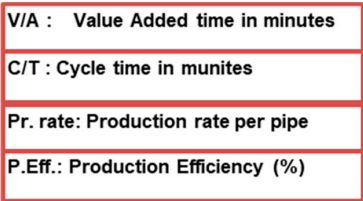
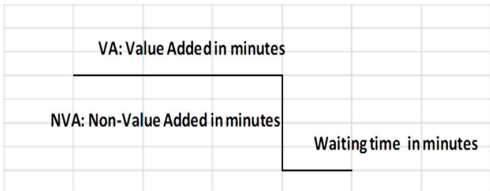




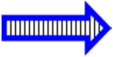

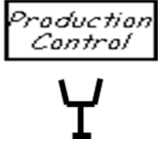



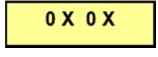
Symbol/Icon	Meaning and Description
	Customer/Supplier Icon: represents the Supplier when in the upper left, customer when in the upper right, the usual end point for material
	Manpower Icon: represents skilled manpower. Shows the number of manpower required to process the VSM family at a particular workstation
	Dedicated Activity flow Icon: a process, operation, machine or department, through which material flows. Represents one department with a continuous, internal fixed flow.
	Data Box Icon: it goes under other icons that have significant information/data required for analysing and observing the system.
	Timeline Icon: shows value added times (Cycle Times) and non-value added (wait) times. Use this to calculate Lead Time and Total Cycle Time.
	Inventory Icons: show inventory and waiting time between two activities/processes.
	Electronic Info Icon: represents electronic flow such as electronic data interchange, the Internet, indicate the frequency of information/data interchange.
	Manual Information Icon: A straight, thin arrow shows general flow of information from memos, reports, or conversation. Frequency and other notes may be relevant.
	FIFO Lane Icon: First-In-First-Out inventory. Use this icon when processes are connected with a FIFO system that limits input.

Table A1. Cont.

Symbol/Icon	Meaning and Description
	Push Arrow Icon: represents the “pushing” of material from one activity to the next activity.
	Kaizen Burst Icon: used to highlight improvement needs and plan kaizen workshops at specific activities that are critical to achieving the Future State Map of the value stream.
	Kanban Post Icon: a location where kanban signals reside for pickup. Often used by a central production scheduling or control production department.
	Withdrawal Kanban Icon: represents a device that instructs a material handler to transfer parts from a supermarket to the receiving process. He goes to the supermarket and withdraws the necessary items.
	Supermarket Icon: an inventory “supermarket” (kanban stockpoint) with a “Pull” icon that indicates physical removal.
	Production Kanban Icon: triggers production of a predefined number of parts. Signals a supplying process to provide parts to a downstream process.
	Load Leveling Icon: a tool to batch kanbans in order to level the production volume and mix over a period of time.

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