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DEVELOPING BALANCED PRODUCTION FLOW: A SIMULATION ON MURA REDUCTION VIA LINE OF BALANCE

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ABSTRACT

Mura (unevenness) is one of the three fundamental wastes in lean thinking, along with Muda (waste) and Muri (overburden). In construction, Mura appears as irregular resource allocation, unpredictable durations, and unstable workflows that disrupt flow and reduce productivity. While Mura has been widely discussed in lean construction, fewer studies use Line of Balance (LOB) to quantify and visualize unevenness across repetitive work, which limits practical, schedule-based assessment. This study investigates Mura using a simulation that replicates pipe-laying operations. Two cycles are compared: one with unbalanced labor and one applying lean principles such as redistribution of resources and standardization. LOB is used to represent production rate and workflow stability across locations, allowing unevenness and its reduction to be observed directly. Results show that addressing Mura improves flow reliability and overall project performance, supporting more efficient construction planning for repetitive operations.

KEYWORDS

Mura, lean construction, flow, simulation, line of balance.

INTRODUCTION

Lean thinking, derived from the Toyota Production System (TPS), centers on eliminating three types of waste: Muda (non-value-adding activities), Muri (overburden), and Mura (variability or unevenness). These three categories of waste are deeply interconnected; Mura can lead to both Muri and Muda (Liker, 2004; Ohno, 1988). While Muda, the tangible, measurable wastes such as excess inventory and overproduction, has received predominant attention in lean thinking (Womack & Jones, 1997), the equally important but less visible issue of systemic unevenness, Mura, often receives minimal attention in practice (Hines et al., 2004). Recent research within the construction sector underscores the critical impact of Mura on the performance and reliability of production systems, emphasizing its systemic and disruptive consequences (Power et al., 2023).

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Mura presents itself in the form of inconsistent cycle times, irregular delivery schedules, uneven workload distribution among crews, and frequent fluctuations in resource availability. These manifestations can significantly interrupt the workflow and lead to downstream inefficiencies and waste (Tommelein & Emdanat, 2022). Unlike Muda and Muri, which are more easily identifiable and measurable, Mura is systemic and can be difficult to isolate. In response, lean practitioners have increasingly turned to tools like takt-time planning and Line of Balance (LOB) scheduling to address flow variability (Aisyah et al., 2025). A common manifestation of Mura in construction is variability in task durations and in the timing of work release between crews (Ballard & Tommelein, 2021). Uneven production across crews and locations is a common reason repetitive work loses flow. When work rates do not match, waiting grows even if each crew is working hard. Takt planning and Line of Balance support flow in different ways. Takt planning sets a target pace for releasing work so trades move through zones with a steady rhythm (Formoso et al., 2025). Line of Balance (LOB) shows actual production rates by location, so differences in pace across trades appear as different line slopes (Sterzi & Bonesi, 2024). In repetitive, location-based work, this slope mismatch is a direct visual signal of unevenness (Mura) and of handoff problems such as waiting and stacking (Formoso et al., 2022). Because the learning goal of this simulation is to make rate mismatch and handoff gaps visible on a location-based chart, this paper focuses on LOB (Pereira et al., 2022). Takt can still be used as a target pace line, and future runs can add a simple takt-like target to compare "planned rhythm" versus "observed rhythm" (Tommelein & Emdanat, 2025).

Pedagogical approaches to lean construction have increasingly emphasized experiential learning through simulations and games. Participants can immediately observe the consequences of their decisions, which reinforces learning through practice (Bhatnagar et al., 2023; Cisterna et al., 2021). In addition to the games Parade of Trades and LEGO Airplane showing clear connections to LOB, there is still a need to test LOB-based unevenness assessment through a new simulation that is designed specifically around repetitive workflow and rate control. The simulation developed by Yaw et al. (2020) is one of the few to address this directly, providing participants with scenarios that replicate the consequences of inconsistent handoffs, crew delays, and rework.

In summary, three major gaps can be identified: Conceptual Gap: There is a limited understanding of how Mura uniquely manifests in construction. Unlike manufacturing, construction is characterized by dynamic, one-time project environments with constantly shifting constraints (Shuvo & Lu, 2020). Tool Gap: Traditional scheduling tools like CPM do not effectively visualize or manage variability. Alternatives such as LOB and takt-time planning offer improved capabilities but are not yet widely adopted across the industry (Zolfaghar Dolabi et al., 2014; Tommelein & Emdanat, 2022). Pedagogical Gap: Apart from Parade of Trade and LEGO Airplane games, many lean training simulations focus on Muda and Muri, overlooking the impact of Mura on system performance. As a result, learners may lack the tools and experience to manage variability effectively (Rybkowski et al., 2021; Bhatnagar et al., 2023).

This paper presents a pilot classroom simulation to enhance understanding of critical lean concepts, focusing on Mura as rate mismatch and uneven handoffs in repetitive work. The main contribution is a simulation setup that lets participants experience uneven flow and then improve it through targeted changes. The paper also proposes a simple way to describe Mura in LOB by linking task productivity rate matching to LOB slope patterns across trades.

METHODOLOGY

This study developed and facilitated a classroom simulation to compare workflow performance across two rounds of a pipe-laying process: Round 1 (baseline, trade-by-trade work with limited coordination) and Round 2 (lean-inspired changes). The simulation replicates a common sequence in underground pipeline installation: excavation, pipe fitting, pipe laying, and

backfilling. The simulation has two 15 to 20 minute rounds and takes up to 1 hour and 15 minutes, including an end-of-simulation debrief discussion where participants provided plus/delta feedback. The simulation was designed to highlight how unevenness in workload, task transitions, and labor distribution can be improved using the LOB scheduling method.

EXPERIMENTAL DESIGN

The simulation was organized into four groups, each comprising eight graduate students from the construction management program, so the sample is small and the analysis is descriptive. The results are reported to show patterns in flow behavior and handoffs within the simulation setting, not to make statistical claims or to represent field productivity. The simulation was designed to offer a semi-realistic portrayal of an underground pipe running operation and was conducted in two rounds to represent initial variability and subsequent improvements.

Round 1

Round 1 served as the baseline condition and operated under a rigid, task-specific structure emulating traditional construction practices. The simulation was divided into four distinct steps such as excavation, pipe fitting, pipe laying, and backfilling. Each participant was limited to their defined role and was not permitted to assist teammates in the activity. Within each team of eight participants, two members performed each distinct step.

Step 1-Excavation: Participants folded 12 pieces of 21.59×25.4 cm paper into U-shaped trench segments and connected them with tape (Figure 1).

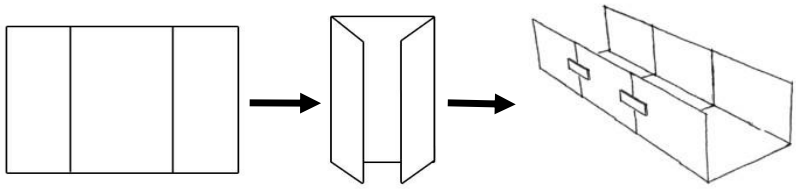


Figure 1: Excavation (Trench Simulation)

Step 2-Pipe Fitting: Participants pinched and joined 20 drinking straws (7.62 cm each) end-to-end into a linear chain (Figure 2).



Figure 2: Pipe fitting through pinching the straws inside each other

Step 3-Pipe Laying: Participants placed joined straw pairs into the trench chain and taped them at junctions (Figure 3).

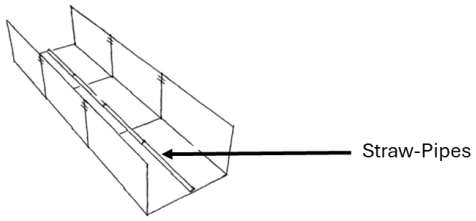


Figure 3: Pipe laying in the trenches using a pair of straws

Step 4-Backfilling: Participants folded 6 pieces of 12.7×25.4 cm paper along the longer side to create a gatefold cover and placed them over the trench with tape (Figure 4). The gatefold design allowed backfilling to proceed faster than excavation, deliberately introducing a rate mismatch.

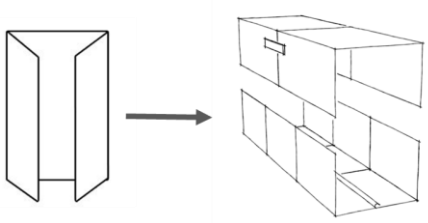


Figure 4: Backfilling by using folded papers in the longitudinal direction

Round 2

Round 2 introduced lean-inspired changes to improve flow, reduce waste, and strengthen teamwork. The task sequence and work quantity stayed the same as Round 1, but two planned changes were made. First, stapling replaced taping both sides of the paper in the excavation step (Step 1). Second, one participant was reassigned from pipe fitting to excavation, so excavation increased from two to three participants and pipe fitting decreased from two to one, while pipe laying and backfilling remained at two participants. Team members were encouraged to support each other during all steps to reduce handoff delays and keep work moving. Because the same scope was repeated and roles were not rotated between rounds, Round 2 improvements reflect both the planned changes and familiarity with the process. For that reason, results are reported as a pilot comparison and interpreted with support from the debrief feedback.

RESULTS

ROUND 1

Table 1 represents a benchmark of the performance metrics from a live play of the Mura simulation, including completion time and productivity rate of each activity for each group that executed Round 1. These values highlight the impact of process inefficiencies stemming from uneven task distribution, manual taping, and limited task roles. Line of Balance (LOB) charts preprogrammed in Excel were used to visualize production flow across activities and teams. The chart slope reflects the production rate, and the spacing between lines reflects waiting and a lack of synchronization.

The LOB analysis for Round 1 reveals distinct variations in production rates and workflow synchronization among the four teams. Team 2 demonstrated the highest level of efficiency, achieving a total duration of approximately 6.35 minutes. This performance is characterized by steep production slopes and tight buffers, indicating a well-synchronized handover between tasks. Conversely, Team 4 exhibited the lowest productivity, with a total duration exceeding 11 minutes; this was primarily driven by the lower production rates in the excavation and

backfilling phases. This led to uneven work distribution and excessive idle time, as shown in Figure 5.

Table 1: Summary of Team Productivity Metrics for Round 1

	Task	Team Size [person]	Work Quantity [cm]	Total Duration [min]	Productivity Rate [cm/min]
TEAM 1	Excavation	2	152.4	3.39	44.96
	Pipe Fitting	2	152.4	1.17	130.26
	Pipe Laying	2	152.4	1.37	111.24
	Backfilling	2	152.4	1.48	102.97
TEAM 2	Excavation	2	152.4	2.58	59.07
	Pipe Fitting	2	152.4	1.43	106.57
	Pipe	2	152.4	1.10	138.55
	Backfilling	2	152.4	1.24	122.9
TEAM 3	Excavation	2	152.4	3.44	44.30
	Pipe Fitting	2	152.4	1.14	133.68
	Pipe Laying	2	152.4	2.04	74.71
	Backfilling	2	152.4	2.28	66.84
TEAM 4	Excavation	2	152.4	4.13	36.9
	Pipe Fitting	2	152.4	1.17	130.26
	Pipe Laying	2	152.4	2.43	62.72
	Backfilling	2	152.4	3.54	43.05

ROUND 2

Table 2 shows that Round 2 increased production rates, but teams still struggled to match rates across activities, which kept bottlenecks and idle time in the workflow. Team 2 achieved the most balanced workflow, maintaining consistent rates between 134.87 and 152.4 cm/min, which minimizes bottleneck risks. Conversely, Team 4 exhibited extreme volatility, reaching peaks of 262.76 cm/min but slowing to 47.92 cm/min during excavation and pipe laying. This imbalance suggests significant idle time between tasks. While Team 1 and Team 3 showed moderate consistency, Team 1's excavation rate (72.57 cm/min) remained a primary constraint. Ultimately, these disparities indicate that while individual task speeds improved, the lack of rate-matching remains a barrier to a lean construction flow.

Production Rates and Workflow Synchronization

The performance metrics and LOB charts for Round 2, as shown below in **Error! Reference source not found.**, illustrate a general increase in productivity compared to Round 1, while simultaneously highlighting distinct differences in workflow synchronization. Team 2 emerged as the most efficient, completing the sequence in approximately 4.3 minutes. Their production rates remained exceptionally consistent, ranging from 134.87 cm/min to 152.4 cm/min, which is visually confirmed by the near-parallel slopes in their LOB chart. This parallelism indicates a balanced rhythm that minimizes work-in-progress (WIP) and idle time.

In stark contrast, Team 4 exhibited the highest degree of unevenness; despite reaching peak productivity rates of 262.76 cm/min during pipe fitting and backfilling, their overall progress was severely constrained by excavation and pipe laying phases at 47.92 cm/min. The resulting LOB chart for Team 4 shows sharp discrepancies in line slopes, signifying a fragmented workflow where rapid completion of intermediate tasks leads to significant bottlenecks at slower stages. While Team 1 and Team 3 showed improved speed, Team 1's excavation rate of 72.57 cm/min remained a primary bottleneck, extending their total duration to approximately 5.5 minutes.

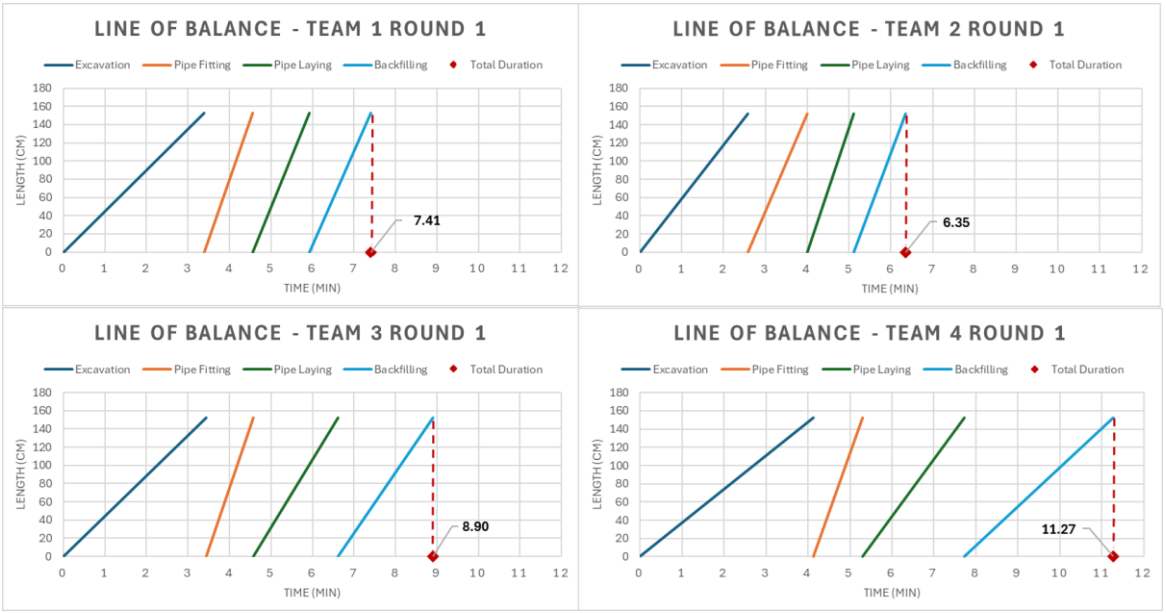


Figure 5: Line of Balance (LOB) Scheduling Profiles for Round 1 across Teams 1-4

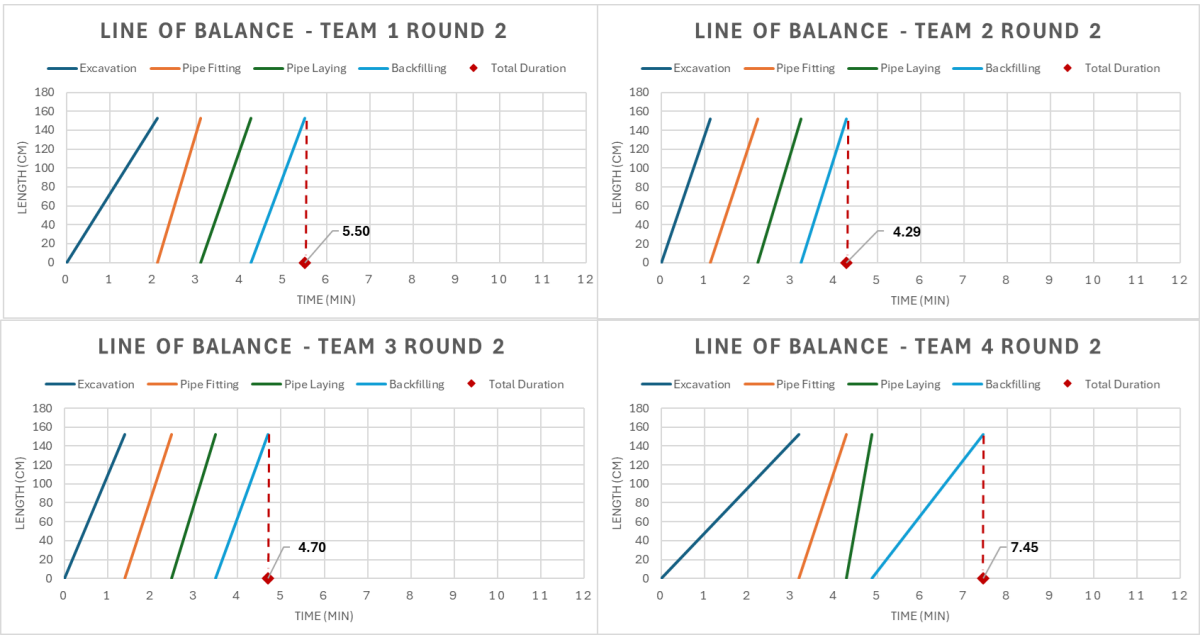


Figure 6: Line of Balance (LOB) Scheduling Profiles for Round 2 across Teams 1-4

Table 2: Summary of Team Productivity Metrics for Round 2

	Task	Team Size [person]	Work Quantity [cm]	Total Duration [min]	Productivity Rate [cm/min]
TEAM 1	Excavation	3	152.4	2.1	72.57
	Pipe Fitting	1	152.4	1	152.40
	Pipe Laying	2	152.4	1.15	132.52
	Backfilling	2	152.4	1.25	121.92
TEAM 2	Excavation	3	152.4	1.13	134.87
	Pipe Fitting	1	152.4	1	152.40
	Pipe	2	152.4	1.13	134.87
	Backfilling	2	152.4	1	152.40
TEAM 3	Excavation	3	152.4	1.4	108.86
	Pipe Fitting	1	152.4	1	152.40
	Pipe	2	152.4	1.4	108.86
	Backfilling	2	152.4	1	152.40
TEAM 4	Excavation	3	152.4	3.18	47.92
	Pipe Fitting	1	152.4	0.58	262.76
	Pipe	2	152.4	3.18	47.92
	Backfilling	2	152.4	0.58	262.76

COMPARATIVE ANALYSIS: IMPROVEMENTS FROM ROUND 1 TO ROUND 2

Time Improvement

The cross-team comparison of time improvements, as shown in Figure 7, reveals diverse learning trajectories and varying levels of process optimization across the four groups. Most teams achieved their most significant efficiency gains in the excavation phase, with Team 3 leading at a 59% reduction, followed by Team 2 at 56% and Team 1 at 38%. A notable outlier in this trend is Team 4, which realized a massive 76% time improvement in pipe laying, representing the highest single-task gain recorded across all participants. In contrast, the pipe fitting phase consistently demonstrated the lowest rates of improvement across the board; both Team 3 and Team 4 saw only a 5% reduction in this category, suggesting that this task may have reached a technical threshold where further repetition yields minimal speed benefits. These results confirm a general learning effect, as teams successfully condensed their work sequences and reduced total project durations from Round 1 to Round 2. However, the variation in improvement percentages indicates that while some teams prioritized speed in initial tasks like excavation, others made their greatest breakthroughs in intermediate stages like pipe laying.



Figure 7: Comparison of time improvement for each activity per team 1-4 between the two rounds

Overall Simulation Time Improvement

The comparison of total project durations between the two rounds is shown in Figure 8, demonstrating a clear trend of enhanced efficiency across all four participating groups. As illustrated in the overall simulation time chart, Team 3 achieved the most significant absolute improvement, reducing their total duration from 8.9 minutes in the first Round to 4.7 minutes in the second. Team 4, which recorded the longest initial completion time of 11.27 minutes, successfully lowered its project duration to 7.45 minutes. Furthermore, the consistency shown by Team 2, which completed Round 2 in only 4.29 minutes, represents the peak efficiency reached during the simulation. This group maintained the most balanced workflow, which minimized the idle time between sequential tasks such as pipe laying and backfilling.

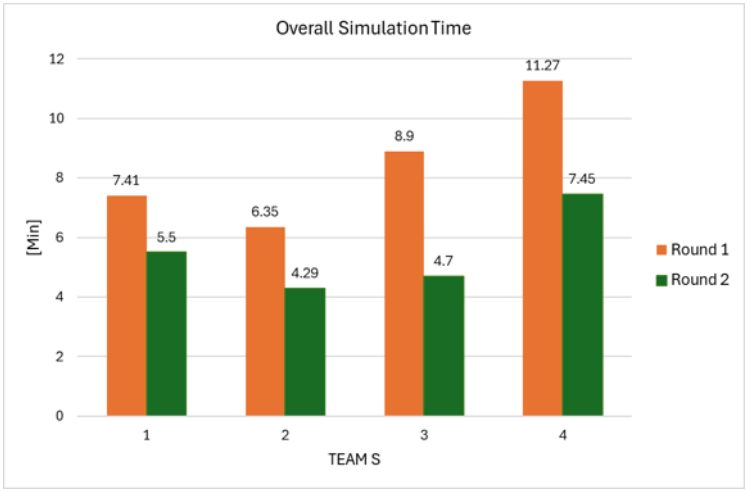


Figure 8: Comparison of overall simulation times for teams 1 through 4 between Round 1 and Round 2.

Productivity Improvement

Figure 9 shows that productivity gains between rounds were driven by both resource changes and learning. The biggest increases were in excavation, where productivity rose by 146% for Team 3 and 128% for Team 2 after increasing the crew from two to three people. Pipe fitting had the smallest gains, with only 5% to 6% improvement for Teams 3 and 4, even though the

crew was reduced from two people to one, suggesting higher individual efficiency. Team 4 stood out in pipe laying, with a 319% increase despite no change in team size, pointing to a clear change in how the task was done.

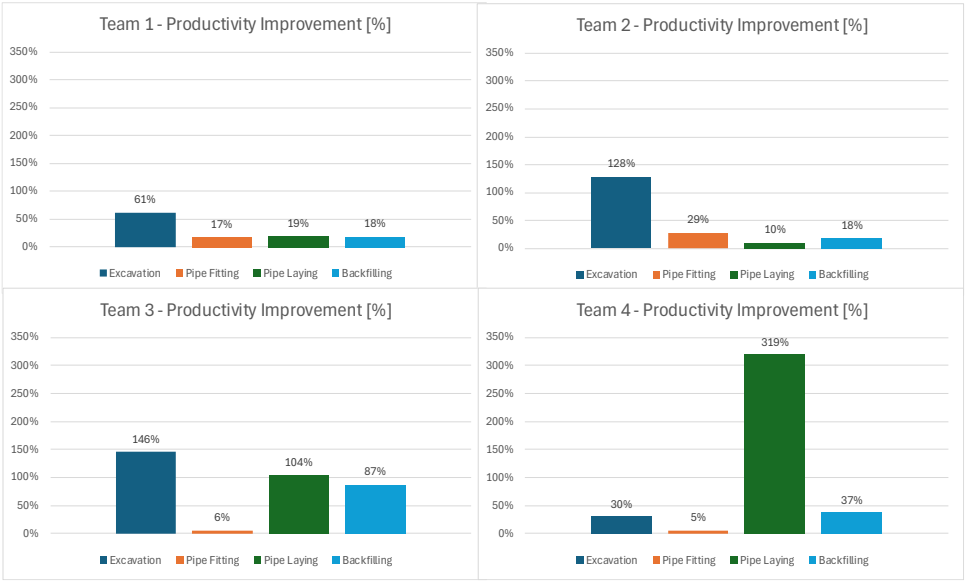


Figure 9: Comparative percentage of productivity improvement for teams 1-4 in both rounds

Rate Matching Ratio (RMR) and Coefficient of Variation (CV) Improvement

To quantify unevenness (Mura) within each team, two measures were computed from the activity productivity rates in each round: the Rate Matching Ratio (RMR) and the coefficient of variation (CV). RMR was calculated as the minimum activity productivity divided by the maximum activity productivity within the same team and round; values closer to 1.0 indicate better rate matching across activities. CV was calculated as the standard deviation divided by the mean of the four activity productivity rates; lower CV indicates less spread in pace across activities. Figure 10 shows that Teams 1–3 improved rate matching from Round 1 to Round 2 and reduced variability. Team 4 showed the opposite pattern (RMR decreased from 0.28 to 0.18 and CV increased from 0.63 to 0.78), indicating that Round 2 changes did not improve rate matching for that team even if one activity became faster.

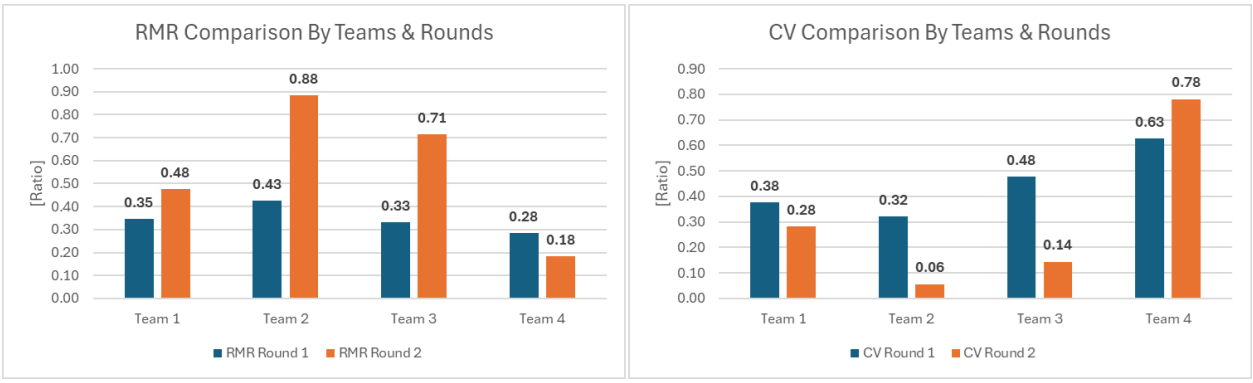


Figure 10: Lean flow metrics: RMR and CV computed from activity productivity rates.

DISCUSSION

Round 2 showed better overall performance than Round 1 for all four teams, with shorter total completion time and fewer interruptions, which points to improved coordination and reduced waiting as key drivers. This pattern is consistent with the comparative activity results in Figures

7 and 9, where the largest percent gains appear in handoff-dependent steps that were more vulnerable to misalignment in Round 1, and it also matches the Line of Balance view that suggests smoother flow and more stable pacing across teams. The RMR and CV results support the LOB interpretation; teams with higher RMR and lower CV had more aligned pacing across activities and smoother handoffs, while Team 4's lower RMR and higher CV match the observed slope mismatch and uneven flow. Participant Plus feedback supports this interpretation. These reflections came from the end-of-simulation debrief discussion. In that discussion, participants consistently described waiting and handoff timing as the main source of delay in Round 1, and they linked smoother Round 2 performance to better rate matching across activities rather than to speeding up a single task. This supports the interpretation that reduced unevenness improved flow mainly through fewer handoff interruptions. Students emphasized that the simulation made resource allocation and coordination between trades visible, and they connected standardization of the work process to improvement. Several participants also noted that the game was simple, clear, and realistic enough to relate to a site situation, and that the team kept the group engaged. They also highlighted that using a timer improved time consistency compared to individuals tracking their own time.

Delta feedback points to clear improvements for future iterations and highlighted where results may reflect both learning effects and design choices. Participants suggested adding a short practice round, clarifying rules, and improving material quality so the trench and task actions behave more consistently. Others noted uneven work distribution within teams and suggested tighter role definitions. They also recommended stronger measurement and outcomes: calculating pace as a simple takt-like target, improving tracking for measures like weight where relevant, and comparing the quality of the final product rather than reporting outcomes mainly as time-based. Some participants also suggested reducing the number of changing factors so the results isolate fewer variables per round, and adding qualitative observations to capture teamwork and coordination behaviors. Finally, participants proposed testing tool changes such as using a stapler instead of tape for backfilling, and possibly testing the effect of stapler use in both excavation and backfilling to examine how tool choice shifts cycle times and handoff balance. The delta points reported in this paragraph were captured during the end-of-simulation debrief discussion with participants. This study reports time and flow outcomes, which relate to efficiency, but effectiveness is different. A team can finish faster and still produce poor output if the final product has defects or needs rework.

CONCLUSION

Round 2 reduced unevenness and improved flow across teams, leading to shorter overall completion time and higher productivity. Excavation showed the largest gains, while pipe fitting improved the least and continued to constrain progress. Teams that prioritized rate matching and clear role allocation produced more stable workflows than teams that focused on accelerating one activity. Because the activity is a simplified classroom simulation with a small number of teams and manual timing, the results should be interpreted as evidence about flow behavior and handoffs, not as direct field productivity values. This study is limited by the classroom setup, small sample size, and manual timing, and we did not compare final product quality, so the results mainly reflect flow and handoffs. Future rounds should keep the learning goal focused on flow and handoffs, add a simple quality check, use a simple takt-like pace target, and improve measurement using automated time capture. Rather than removing variation, future runs should keep some variation in materials and team behavior on purpose and use the debrief discussion to unpack how that variation affects handoffs, waiting, and rate matching. More rounds can then help connect unevenness and waiting to cost-related outcomes such as labor idle time and rework.

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