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RESEARCH ARTICLE

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Lean Transformation in Vocational Engineering Education: Identifying and Mapping Waste Through Value Stream Mapping

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ABSTRACT

This study maps waste and identifies the determinants of inefficiency in the lost-PLA metal casting practicum and examines the learning outcomes associated with a waste-aware practicum developed from that map. A mixed-method design was used. The first phase involved 66 students completing a 40-item questionnaire on twelve practicum stages; categorical durations were converted into minutes and each stage was classified as value-added, non-value-added, or necessary non-value-added. The second phase used a non-equivalent control group design with 85 students, 28 in the control class and 57 in two treatment classes, over four meetings. Learning outcomes were measured with a 20-item test administered one month apart. Analysis employed bottleneck ranking, the seven-waste framework, Spearman correlation with Holm correction, normalised gain, Kruskal-Wallis, and Mann-Whitney tests. Waiting dominated the measured waste profile at 64.0%, concentrated in machine and furnace queues. Pattern design and printing was the main bottleneck at 57.3 minutes against a required pace of 45 minutes per unit, of which 38.8 minutes were waiting. Finishing, cooling, and melting were the strongest determinants of perceived inefficiency. The treatment classes reached a normalised gain of 0.723 against 0.226 in the control class. Waste in the casting practicum is structural rather than individual.

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1. Introduction

Vocational education is expected to produce graduates who can perform at a technician's level rather than merely recite procedures [1] [2] . This is institutionalised in Indonesia through the concept of the teaching factory, which is a form of learning based on activities that are organised as if it were a production process [3] [4] [5] . This concept requires that the quality of the practicum is not only measured based on the final scores of the students but also based on the efficiency in the utilisation of the practicum time, equipment and material in building competence [1] [2] . One of the matters that is often neglected and never measured systematically is the waste of time in practicum due to the fact that it is not because the students learn nothing; instead, they are not doing any value adding process. They just wait, repeat or transport the workpieces from one machine to another.

One of the typical processes in which the waste is very visible is the metal casting process. This process has a lot of stages that are highly interrelated, such as the pattern preparation process, making the mould, curing the mould, burning the mould, melting the metal, pouring, cooling, shakeout and surface finishing. The availability of different equipment also plays a crucial role in this process. One of the variants of the casting process, known as the lost PLA casting process, is a process where the casting mould is made using the investment casting process using the pattern that is made by 3D printer[6] [7] Studies on polylactic acid patterns mostly optimise the casting process parameters [6] [7] , and research on the use of other types of patterns or the lost foam casting process usually discusses technical issues but not the queuing phenomenon that arises as a pedagogical consequence[8] [9] . By using only a few 3D printers, burnout furnaces and melting furnaces, queues are formed that are not captured by learning outcome measurement but directly affect the practicum activities.

The value stream mapping concept provides the framework to analyse the problem. The framework separates activities that add value from those that do not, measures waiting time, and places bottlenecks in a position where they can be acted upon [10] [11] . It has been used to optimise manufacturing processes [12] , to evaluate process cycle efficiency in logistics [13] , and to integrate process representation with business process modelling [14] . It has also been extended to the service sector and to education, including the mapping of academic processes and administrative services [15] [16] . In the Indonesian context, lean and value stream mapping have been applied to production processes in small enterprises and to the evaluation of non-value-added activities[17] [18] . Several studies have placed lean in vocational high schools and vocational education institutions [19] [20] , and the readiness of higher education institutions to adopt lean has been examined as well [21] .

Three gaps nevertheless remain open. Firstly, most of the studies in lean implementation in education focused in lean implementation in service process while neglecting lean implementation in laboratory learning process[22] , although the condition in a laboratory queue is similar with the production floor queue. Secondly, most of the lean implementation studies in education did not conduct beyond current state mapping and neglect the impact of the process improvement towards the learning outcome. Thirdly, few empirical studies about lean implementation in vocational education in Indonesia are available, even though practicum workload and equipment to student ratio are critical aspects in vocational education in Indonesia.

These three gaps are interrelated and stem from similar methodological considerations. Value stream mapping (VSM) gives priority to problems that take more time, however the student sees a practicum as a mixture of waiting time, working time, and uncertain quality [15] [23] . Thus, when the improvement effort is only based on time, there is a possibility that valuable laboratory time will be used for a stage that has been internalised by students without being able to touch the stages that erode the learning experience [16] [17] . This misalignment between perceptions and objectives has obvious implications for vocational training programmes in which allocation is made in terms of laboratory sessions [19] [21] . In order to address the misalignment, we propose to implement an objective process map combined with a student assessment of the process. This idea constitutes the objective of this study.

The three objectives of this study are: (1) to use a current-state value stream map to assess and classify the activities involved and identify bottlenecks in order to map waste in the lost-PLA metal casting practicum; (2) to identify the stages in the lost-PLA metal casting practicum that most impact students' perception of inefficiency; and (3) to examine the learning outcomes associated with a waste-aware practicum developed from that map, taking into account an untreated class for comparison. Three hypotheses follow from these objectives. Waiting is expected to be the dominant waste category (H1a) and to originate in equipment capacity rather than in student behaviour (H1b); the stages with the highest problem scores are expected to be the strongest determinants of perceived inefficiency (H2); and a practicum organised with an awareness of waste is expected to be associated with a higher normalised gain than a conventional practicum (H3). This study makes both methodological and practical contributions. Methodologically, it uses value stream mapping as a diagnostic tool for practical learning. In practical terms, it provides a basis for prioritizing improvements in the casting laboratory.

2. Method

2.1 Research design

The study used a mixed-method design in two phases. The first was descriptive-exploratory and mapped waste in the practicum as it was then conducted. The second was a quasi-experiment evaluating the learning outcomes of a waste-aware module developed from that map, so the diagnosis informed the design and the design was then tested. Because the module did not exist before the study, the first phase describes the conventional condition against which it was compared.

The module's features follow from the constraints the map identified: scheduled rather than first-come access to the three printers; a fixed rotation for the single burnout and melting furnaces; and redirection of released time to structured observation, dimensional inspection and defect analysis during cooling and finishing. Table 1 links each feature to the VSM finding that motivated it. Because the module was delivered as a package, the study cannot isolate the active ingredient.

Waste-aware feature	Related VSM finding	Expected mechanism
Scheduled rather than first-come access to the three printers	Printing queue of 38.8 minutes; stage duration of 57.3 minutes against a required cycle time of 45 minutes	Reduces waiting before printing and allows groups to move to mould preparation
Fixed rotation for the single burnout and melting furnaces	Queues at the burnout and melting furnaces, which rank second and third as bottlenecks	Prevents groups from accumulating at one furnace and stabilises the session sequence
Structured observation, dimensional inspection, and defect analysis during cooling and finishing	Melting, cooling, and finishing as the strongest correlates of perceived inefficiency	Converts otherwise idle waiting time into value-adding learning activity

2.2 Participants

The population was fifth-semester students of the Mechanical Engineering Education study programme, Faculty of Engineering, Universitas Negeri Malang, enrolled in the 2026 metal casting practicum. The mapping phase involved 66 respondents from four parallel classes (A1 = 15, A2 = 3, A3 = 24, A4 = 24). Class A2 contributed only three respondents and later served as the control group, so class-specific perception scores may not represent the control condition; because the class-level subsamples were too small for stable comparison, the mapping results describe the practicum as a whole. Class A2 accounts for 4.5% of the mapping sample and classes A3 and A4 together for 72.7%. The experimental phase involved 85 students in three intact classes: A2 as control (n = 28), A3 (n = 28) and A4 (n = 29) as treatment groups. Classes were not randomly assigned, so a non-equivalent control group design was used over four sessions of five lesson hours. The sensitivity of the mapping results to this imbalance is reported in Section 3.1.

2.3 Instruments

The first-phase instrument was a 40-item questionnaire covering twelve practicum stages. Duration items used ordered categories (under 10, 10–20, 21–30 and over 30 minutes) converted to minutes at the category midpoint, with the open-ended category coded as its lower limit multiplied by 1.25. Equipment adequacy, repetition frequency and problems encountered were measured by non-duration items coded 1 to 4, a higher code denoting a more problematic condition.

2.4 Data analysis

The first phase was analysed in four steps. Stage duration was summed from the time items, and each stage was classified as value-added, non-value-added or necessary non-value-added. Bottlenecks were determined by ranking the twelve stages on three criteria and ordering them by the unweighted average of those ranks, the lowest average receiving rank one. Duration is the summed time items in minutes and expresses lost time. The percentage of problematic responses is the share of respondents choosing code 3 or 4 on each problem item, averaged across the items of a stage, and expresses how often the stage is experienced as a problem. The composite stage score is the mean of every item of the stage on the 1 to 4 scale and expresses the intensity of the problem. The composite therefore shares the duration items with the duration criterion and is not fully independent of it; Section 4.4 examines the consequence. The three criteria carry equal weight, fixed before the rankings were inspected because no empirical or theoretical ground exists for privileging one, since each captures a distinct property: lost time, problem frequency and problem intensity. Because all three ranks share the same 1-to-12 scale, their arithmetic mean needs no further standardisation. Waste was mapped onto the seven-waste framework, and stage-level associations with perceived inefficiency were tested by Spearman correlation corrected with the Holm method for twelve tests. The second phase used normalised gain [24], Kruskal-Wallis and Mann-Whitney; analysis of variance checked pretest equivalence, and analysis of covariance was rejected because homogeneity of

slopes failed and the posttest showed a ceiling effect. H1a was evaluated by the waste profile, H1b by the bottleneck ranking with the equipment-to-group ratio, H2 by the rank correlations and H3 by the between-class comparison of normalised gain.

2.5 Cycle time and laboratory capacity

The required pace is capacity-based rather than demand-based. A session lasts 225 minutes and accommodates five groups producing five units, so one unit must be completed every 45 minutes. The laboratory has three printers, one burnout furnace and one melting furnace. Five patterns over three printers require two printing rounds, and each furnace processes one batch at a time, so queues form before burnout and melting. Because parallel capacity differs by stage, a duration above 45 minutes is not by itself evidence of a bottleneck, which is why Table 2 combines duration, problem frequency and the composite score.

3. Results

3.1 Value stream map and bottleneck

Value stream mapping identified twelve stages and twenty-five processes (Figure 1), with durations, classifications and ranks in Table 2. One unit required 503.3 minutes, or 8.4 hours. Durations ranged from 17.3 minutes at shakeout to 71.1 minutes at cooling.

Figure 1. Current-state value stream map of the lost-PLA metal casting practicum

Stage	Duration (min)	Explicit waiting (min)	Problematic responses (%)	Classification	Bottleneck rank
Pattern design and printing	57.3	38.8	53.5	VA+NVA	1
PLA pattern finishing	20.6	–	37.1	VA	4
Sprue and riser assembly	17.5	–	24.2	VA	11
Mould making	35.5	–	36.4	VA	7
Mould curing	56.5	–	24.2	NNVA	9
Burnout	63.5	–	42.4	NNVA	2
Metal melting	40.1	–	40.9	VA	3
Pouring	19.5	19.5	28.0	NVA	10
Cooling	71.1	–	19.7	NNVA	6
Shakeout	17.3	–	–	VA	12
Finishing of cast products	44.5	–	28.8	VA	8
Rework	59.9	–	28.8	NVA	4

Note. VA = value added; NVA = non-value added; NNVA = necessary non-value added [25] [11]. Stages are ordered by the unweighted average of the duration, problematic-response and composite-score ranks; component ranks appear in Table S1. Pattern finishing and rework share an average of 5.33 and both occupy rank four, leaving rank five unused. Durations are respondent estimates. Pattern design and printing is VA + NVA because 38.8 of its 57.3 minutes are waiting, and pouring is NVA because all 19.5 minutes are waiting.

Pattern design and printing ranked first (57.3 minutes, 38.8 of them explicit waiting). Because three printers serve five groups, the stage requires two printing rounds; the mismatch, not the duration alone, makes it a bottleneck. Burnout and metal melting ranked second and third, both constrained by a single furnace. Cooling was the longest stage (71.1 minutes) but ranked sixth, because unavoidable waiting is not a controllable bottleneck. Value-added time was 194.0 of 503.3 minutes, a process cycle efficiency of 38.5%. Without class A2 (n = 63), the first three ranks were unchanged and no stage moved by more than two positions.

3.2 Waste profile

Waiting dominated the measured profile at 64.0% of the 264 responses to the four obstacle items, followed by motion, defects and inventory (Table 3). Because the instrument had no transportation or overproduction items, this is a conditional share of four measured categories, not all seven wastes, and it describes how often waiting was reported rather than how much time it consumed. Waiting for the melting furnace, sprue and riser aids and the printing machine were the most frequent obstacles, consistent with an equipment-to group queue rather than individual slowness.

Waste category	Frequency	Percentage	Concrete form
Waiting	169	64.0	Printer, burnout furnace, melting furnace, and aid-tool queues
Motion	52	19.7	Difficulty breaking the mould, positioning during assembly
Defects	24	9.1	Printing failure, assembly error, casting porosity
Inventory	19	7.2	Delayed supply of moulding material

Note. Based on 264 responses to the four obstacle items; percentages are calculated against total responses, so the waiting share is 169 of 264.

3.3 Determinants of inefficiency

Seven stages correlated significantly with perceived inefficiency after Holm correction, with coefficients of determination from 12.2% to 28.4% (Table 4); the strongest were metal melting, cooling and finishing. Pattern design and printing, despite the highest problem score, was not significant ($r = 0.242$; Holm-adjusted $p = 0.184$), so H2 is not supported. This null should be read against reliability: the scale's alpha is 0.547 and perceived inefficiency is a single item, so the coefficient is attenuated and the underlying association is probably stronger, although the main finding is not reversed. Excluding class A2 changes no coefficient by more than 0.042 and leaves the seven stages unchanged.

Rank	Stage	Spearman coefficient	Holm-adjusted p	Coefficient of determination
1	Finishing of cast products	0.533	< 0.001	0.284
2	Cooling	0.504	< 0.001	0.254
3	Metal melting	0.464	0.001	0.215
4	Burnout	0.451	0.001	0.203
5	Sprue and riser assembly	0.416	0.004	0.173
6	Pouring	0.415	0.004	0.172
7	Mould curing	0.349	0.024	0.122

Note. $n = 66$; high scores denote more problematic conditions. The critical value applies to the Holm correction over twelve tests, so these seven stages are the only ones significant after correction.

3.4 Learning outcomes

The three classes were equivalent at pretest (means 60.00, 67.50 and 65.00; $F(2, 82) = 1.504$, $p = 0.228$). After treatment, the treatment classes reached 88 to 90 while the control class rose to 68.04 (Table 5); normalised gain was 0.723 for the treatment classes, classified as high, against 0.226 for the control class.

Group	n	Pretest (M ± SD)	Posttest (M ± SD)	Gain	Normalised gain	Category
Control (A2)	28	60.00 ± 15.69	68.04 ± 15.89	8.04	0.226	Low
Treatment (A3)	28	67.50 ± 17.92	90.00 ± 8.39	22.50	0.725	High
Treatment (A4)	29	65.00 ± 15.75	87.93 ± 10.05	22.93	0.722	High
Combined treatment	57	66.23	88.95	22.72	0.723	High

Note. Normalised gain follows Hake [24]; class means are reported separately from the aggregate gain, and the combined row pools the two treatment classes without standard deviations.

Posttest and normalised gain differed significantly between groups (Table 6). Mann-Whitney showed that the control class differed from both treatment classes with a large effect, while the treatment classes did not differ from each other, so the result was not tied to a single class, supporting H3.

Comparison	Test	Statistic	p	Effect size
Pretest, three classes	ANOVA	$F(2, 82) = 1.504$	0.228	$\eta^2 = 0.035$
Posttest, three classes	Kruskal-Wallis	$H(2) = 30.82$	< 0.001	–
Normalised gain, three classes	Kruskal-Wallis	$H(2) = 49.59$	< 0.001	–
Control vs treatment A3	Mann-Whitney	$U = 14.5$	< 0.001	$r = 0.82$
Control vs treatment A4	Mann-Whitney	$U = 24.5$	< 0.001	$r = 0.81$
Treatment A3 vs A4	Mann-Whitney	$U = 369.5$	0.899	$r = 0.08$
Combined treatment vs control	Mann-Whitney	$U = 39.0$	< 0.001	$r = 0.77$

Note. The effect size r divides z by the square root of the sample size. Because the three pairwise comparisons follow a significant Kruskal-Wallis test, they were Holm-corrected: both control-treatment comparisons remain significant ($p < 0.001$; adjusted $p < 0.003$) and the treatment-treatment comparison remains non-significant ($p = 0.899$; adjusted $p = 0.899$). Bonferroni leaves every conclusion unchanged.

4. Discussion

4.1 Structural waste instead of individual failures

The first finding confirms that waiting time, not student error, is the primary waste. Almost two thirds of obstacle responses concerned queuing at the printer, burnout furnace and melting furnace. Three printers and one furnace for five groups create a queue by capacity rather than chance: five patterns over three printers require two rounds, and the 45-minute pace follows from the session length. Measures aimed at student discipline would therefore have little effect, whereas scheduling and equipment allocation could. This matches evidence that the most prominent waste in higher education originates in processes rather than individual behaviour [17]–[19], and that queue formation and workflow management dominate in vocational settings [25], [26], with institutional readiness determining whether queues reappear [27]. H1a is supported by the waste profile and H1b by the equipment-to-group ratio.

4.2 Objective waste and perceived inefficiency

Pattern design and printing ranked first, yet did not correlate significantly with overall efficiency ratings, whereas melting, cooling and finishing did; H2 is not supported. Part of the missing association is measurement error: the scale's alpha is 0.547 and perceived inefficiency is a single item. Habituation is therefore complementary to a psychometric explanation, and the data cannot separate them, because both predict attenuation and no discriminating measure was collected. Habituation remains plausible: students accustomed to printer queues may no longer register the wait, while problems in manually operated stages that affect cast quality stay visible. A value stream map allocates intervention by time alone, whereas educational analysis must also weight experience, so combining time ranks, problem frequency and perceived inefficiency changes priorities. This extends process mapping combined with modelling [16] into pedagogy and yields a two-track priority list: printing for capacity, finishing and cooling for learning quality.

4.3 Learning gains from a waste-aware practicum

Waste-aware learning was associated with substantially larger gains: normalised gain 0.723 against 0.226, combined effect size 0.77, with treated classes improving by about 22.7 points against 8.0. Pretest equivalence makes initial disparity unlikely, but two threats preclude a causal reading: the control class had a different instructor, and different forms were used at pretest and posttest, so part of the gain may reflect form difficulty. The treatment classes did not differ ($r = 0.08$), so the result is not tied to one class. The most plausible, though unmeasured, mechanism is that queue time was redirected to observing solidification, dimensional inspection and defect analysis; this is consistent with evidence that effective learning time can increase without adding lesson hours [20], [21], and that 3D printing depends on workflow design [28], [29]. H3 is therefore supported only in the associational sense.

4.4 Implications and limitations

Two implications follow. Value stream mapping can diagnose, at the start of a semester, the fit between laboratory facilities and class size. For laboratory management, the duration and perception data indicate where to invest and in what order: printer capacity first, then finishing stations and cooling racks.

The study has four groups of limitations. First, durations were student estimates rather than stopwatch timings, so they support relative rather than absolute comparison, and the instrument lacked transportation and overproduction items. The mapping

sample was uneven (three respondents from A2, later the control class); because class-level subsamples were too small, results describe the practicum as a whole, and excluding A2 (n = 63) left the three leading ranks and seven significant stages unchanged, with no coefficient moving by more than 0.042. Second, six of twelve stage scales had alpha below 0.60, so those scores are indices of a problem and their correlations are attenuated; the 20-item test was more consistent (KR-20 0.647 and 0.735, with A3's 0.408 posttest value depressed by restricted variance). Third, the control class had another teacher and the posttest showed a ceiling effect (seven students at 100), which ruled out analysis of covariance, and item formats differed between forms. Fourth, waiting time was not measured in the treatment classes, so the mechanism is an interpretation rather than a tested pathway.

The equal weighting of the three bottleneck criteria is achoice, not a finding: doubling the weight of duration would place burnout first, pattern design second and cooling third and move melting to fifth, whereas doubling either other weight leaves the top three unchanged. The composite also shares duration items with the duration criterion; using problem items alone left the top three unchanged and moved no stage by more than three positions.

5. Conclusion

For lost-PLA metal casting practical learning, the dominant form of waste, waiting time, is structural rather than behavioural: it originates from the equipment-to-group ratio, in which three 3D printers and one burnout and one melting furnace serve five groups, and not from student indiscipline. Pattern design and printing is the most significant source of activity bottleneck, because five patterns must pass through three printers within a session. Metal melting, cooling the cast products, and finishing them are the major sources of the sense of inefficiency. The finding suggests that while optimising the practical learning process, one should focus on how students perceive it, rather than just the activity time.

Waste-aware practical learning was associated with higher learning outcomes (normalised gain 0.723) than regular learning (normalised gain 0.226) with a large effect size. The consistency of the effect across the two treatment classes suggests that it is not specific to a single class, but the scope for generalisation is narrow: the evidence comes from three intact classes in one institution, a control class taught by a different instructor, and a module whose features are specified only at the level summarised in Table 1. The findings therefore support analytic rather than statistical generalisation: they are transferable to settings with a comparable equipment-to-group constraint in vocational teacher-education programmes, but not to practicum settings in general, and should be tested in other institutions with fully documented modules before any wider generalisation is made. For future studies, using a questionnaire with questions for all types of waste, direct measurement of time, and a data collection methodology separating the treatment effect and the instructor effect are recommended.

Declarations

AUTHOR CONTRIBUTIONS (CREDIT)

CONTRIBUTOR	CREDIT ROLES
Saifuddin Karim	Conceptualization Data curation Funding acquisition Methodology Writing – original draft
Tamara Rahma Widowati	Investigation Data curation Resources Methodology
Dian Julianto Wahyudi	Resources Methodology Validation Visualization Formal analysis
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Mohamad Cahyo Rupianto	Writing – original draft Project administration Writing – review & editing Software Visualization
Keyola Aulia Sudarto	Writing – review & editing Writing – original draft

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CONFLICT OF INTEREST

no conflict of interest

ETHICS STATEMENT

The research protocol was reviewed and approved by the institutional authorities of Universitas Negeri Malang. All participants (instructors, laboratory staff, and students) gave their informed consent prior to their inclusion in the study. Data collection, including observations and video recordings, adhered strictly to the institution's academic and ethical standards

DECLARATION OF GENERATIVE AI USE

During the preparation of this manuscript, the authors used generative AI technologies solely to improve the grammatical structure and English language translation of the text. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the final integrity and accuracy of the publication

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