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Characterizing Waste in Efficient Lean Systems with Proportional Financial Ratios

Sainath Gopinath, Theodor Freiheit
Department of Mechanical and Manufacturing Engineering
University of Calgary, Calgary, Alberta, T2N 1N4 Canada

Abstract

Lean manufacturing emphasizes value creation by waste elimination. How waste contributes to product cost changes with manufacturing system design and waste's contribution to product cost is weighted with cost parameters. Financial metrics are proposed to characterize waste relationships and to calculate proportional ratios. Proportional ratios are dimensionless measures of the relative contribution to total system waste cost in efficient lean systems. They can be used to exploit waste relationships to provide insight into the distribution of product waste cost for better systems design. The financial waste relationships are verified using discrete-event simulation and influential wastes impacting the total waste cost and its variation in system designs is studied with statistically designed experiments.

Keywords
Lean systems, financial metrics, waste relationships, system design classification, design of experiment

1. Introduction

Wastes are non-value added activities that contribute to product cost for which the customer is unwilling to pay. Lean manufacturing emphasizes value creation by eliminating wastes. Eliminating waste can reduce product cost and improve quality, but it is not possible to uproot waste completely even in an efficient system as some systems have waste as a part of their functionality [1]. Understanding waste relationships facilitates minimization of system waste to its lowest possible level.

The degree to which different wastes contribute to product cost changes with respect to the system design. Waste costs should be weighted based on their contribution to the product cost using financial metrics. System proportional ratios (PR) help to classify different system designs and provide necessary information into the distribution of product waste cost variation and influential wastes in efficient lean systems. Proportional ratios are dimensionless measures of the relative contribution of different wastes to total system waste costs.

Womack *et al.* [2] classified wastes in lean manufacturing into seven categories: defects, overproduction, inventory, waiting, processing, motion and transportation. Researchers like Rawabdeh [3], Canel *et al.* [4], Svensson [5], Russell & Taylor [6] unanimously stress waste elimination, as it is purely non-value adding to the product and the customer. Rawabdeh [3] devised a generic waste relationship model which Gopinath and Freiheit [1] extended to examine the trade-off relationship between the wastes in Pareto-optimal waste-dependent lean manufacturing systems. Wastes cannot be eliminated in Pareto-optimal waste-dependent lean systems, but can be decreased to a minimum which requires effective trade-off decisions in order to minimize system wastes.

This paper examines the financial waste relationships driving the distribution of product waste costs in a Pareto-optimal waste-dependent lean system. Financial metrics are developed by multiplying relevant weights (costs) with a non-financial metric set developed by Gopinath and Freiheit [1]. Proportional ratios (PRs) are proposed in this paper to categorize different system designs and provide systematic insight into the distribution of total waste cost variation and the most influential wastes in those designs. The next sections outline the methodology, define the financial metrics and proportional ratios, verify the financial waste relationships, and determine the influential wastes in the different system designs.

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2. Methodology

The lean manufacturing systems literature was reviewed to understand thinking about waste in the existing research and to explore potential financial metrics, determine and develop missing metrics, and examine existing system design classification tools. Second, the proportional ratios were calculated for different system designs using financial metrics in order to develop system classifications. Finally, the contribution of different wastes to total waste cost variation and the influential wastes at different PRs (system designs) was determined using statistically designed experiments.

3. Financial Metrics

The financial metrics, Table 1, are obtained by multiplying the non-financial metric with the respective financial multiplier. The non-financial metrics were obtained from simple, shop floor feasible metrics [1] and are given an appropriate weight for a given system to convert them into waste costs.

3.1. Financial Relationship between the Wastes

The waste relationship model developed by Gopinath & Freiheit [1] was used as a hypothesis for testing financial relationships between wastes. They showed that there is a trade-off relationship between the wastes using Pearson product-moment correlation analysis. It is expected that similar trade-off relationships will be observed because the multiplication of non-financial metrics by constants (costs) should not change the nature of the relationships between wastes. The definition of all of the terms in Table 1 can be found in [1].

Table 1: Financial Metrics

Waste Code	Waste	Metric	Financial Multiplier	Waste Category
A	Defects	$\sum_{all\ MCi}\frac{Si}{P}$	Material Cost	Material
B	Over-Production	$\int_0^T FIdt$	Finished Inventory Holding Cost	Demand
C	Motion	$\frac{T_m}{T}$	Operator Cost	Resource
D	Transportation	$\frac{FT_t}{T}$	Resource Cost	Resource
E	Waiting (Customer)	$\frac{T_w}{T}$	Customer Resource Cost	Demand
F	Waiting (Machine)	$1-\frac{\sum_{all\ MC}T_{Ri}}{nT}$	Resource Cost	Resource
G	Waiting (Operator)	$1-\left(\frac{T_w+T_m}{T}\right)$	Operator Cost	Resource
H	Inventory (Warehouse)	$\int_0^T WHdt$	Holding Cost	Material
I	Inventory (Work in Progress)	$\sum_{all\ WIP}\int_0^T WIP_i dt$	Holding Cost	Material

3.2. Proportional Ratios and System Design Classification

Literature on financial ratios in the context of lean manufacturing and Just-In-Time (JIT) inventory replenishment use financial ratios like return on assets or return on sales, fixed assets turnover, or debt ratio [7-9]. While these ratios are important in making business decisions, they are less useful in classifying manufacturing systems the way dimensionless ratios have been used in other fields of engineering, e.g. how the Reynolds Number is used to classify fluidic systems as laminar or turbulent. Proportional ratios are dimensionless mathematical ratios proposed for the classification of financially weighted waste in different lean system designs. To the best of the authors knowledge, nothing has been published in the area of proportional cost ratios in the context of lean manufacturing.

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The seven lean-defined wastes are grouped logically under the three categories, demand waste (D_w), material waste (M_w), and resource waste (R_w), where total waste (T_w) is their sum, $T_w = D_w + M_w + R_w$. Wastes that are directly connected with the customer like over-production and customer waiting are grouped under demand waste. Wastes associated with inventory like warehouse, defects, and WIP are grouped under material waste. Similarly, wastes associated with resources like machines or operators are grouped under resource waste. Table 1 summarizes the classification of the wastes. These three wastes are divided by the total waste cost to yield their respective ratio.

$$Demand\ Ratio = \frac{D_w}{T_w} \qquad Material\ Ratio = \frac{M_w}{T_w} \qquad Resource\ Ratio = \frac{R_w}{T_w} \tag{1}$$

Different system operational areas can be classified in two-dimensions. Where a system falls within these two dimensions depends on how much of each type of waste is generated and its financial weight (cost) according to product, process and business interactions. Only two PRs are necessary to define the system as the other ratio is automatically determined from the sum of these two PRs. Table 2 is an example of a chart that can be used to classify a system in the material and resource ratio dimensions. Numbers I to VI in the table indicate systems whose relative contribution of the wastes differs according to the proportions shown. For example, high material and resource ratios denote high material and expensive process waste, respectively. A system design with both a material and resource ratio of 0.4 indicates a system that deals with both expensive materials and processes, but less demand waste. Compare a manufacturing system for screws (fasteners) to that of automotive engines. The screw manufacturing system is likely to have a lower resource and material costs compared to an engine manufacturing system. Hence, the engine manufacturing system is likely to have higher resource and material ratio than the screw manufacturing system.

Table 2: Example System Classification Chart

Material Ratio			
0.6	III		
0.4	V	II	
0.2	VI	IV	I
	0.2	**0.4**	**0.6**
		Resource Ratio	

Table 3: Discrete Event Simulation System Parameters

Variables		**System Parameters**	
Batch Size	B1	100	Units
Batch Size	B2	5	Units
Lead Time	LT	600	Min
Distance	D1	5500	Ft
Velocity	V1	265	Ft / min
Scrap	S1	0.2	%
Scrap	S2	0.2	%
Cycle Time	CT1	7.8	Min
Cycle Time	CT2	8.2	Min
Reorder point	ROP1	100	Units
Reorder point	ROP2	15	Units
Availability	A1	95	%
Availability	A2	90	%

4. Statistical Exploration of the Financial Waste Relationships

A discrete-event simulation model and the pareto-optimal system operational parameters suggested by Gopinath & Freiheit [1] were used to verify the financial relationship between the wastes. The waste relationship model was tested using a discrete-event simulation of a simple serial 'pull' manufacturing system model illustrated in Figure 1.

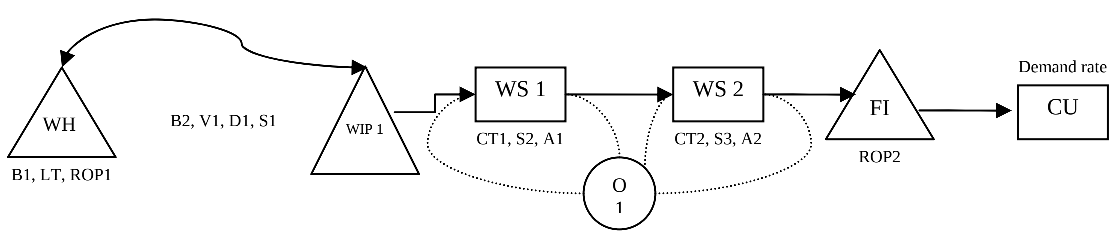

Figure 1: Schematic of the Discrete Event Simulation Model

The system parameters, Table 3, were chosen to be within the Pareto-optimal bounds [1], which were maintained constant throughout the experiments. The model was run for 249,600 minutes of production time (representing one

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year) for thirty replications using Arena®. System performance statistics were collected after a 4800 minute warm-up to avoid the initialization biases. The demand rate was varied by ± 10% with respect to the system takt time. System operational parameters are held constant for all six locations in Table 2 and the cost parameters are changed in order to position the systems appropriately in the system classification chart. Therefore, waste cost mostly determines the location of different system designs in the chart.

4.1. Design of Experiments to Determine Influential Wastes

A resolution III classical design of experiment (DOE) was conducted to understand the effect of cost parameters on the distribution of the waste cost variation. Five trials of the six system operation spots of Table 2 at two different waste cost levels were run in order to establish a 90% confidence interval for the distribution of product waste cost variation. As noted earlier, each spot has a PR value that was achieved by changing the cost parameter weights.

Table 4 shows the distribution of variation in waste costs and their 90% confidence intervals at design spots II and V respectively. For illustration, spot II could be thought of as an engine manufacturing system with a material ratio of 0.4 and resource ratio of 0.4. It accumulates lower inventories when compared to the screw manufacturing system, but utilizes expensive materials and processes. Spot V resembles a screw manufacturing system with a material ratio of 0.4 and resource ratio of 0.2, as this system is likely to have a lower material as well as transformation resource costs, but has the potential for large inventories. It can be seen that transportation and waiting machine resource wastes contribute the most to waste cost variation in both the engine and screw manufacturing systems, but the degree of contribution to each category changes with respect to the system.

Table 5 shows the three largest wastes which contribute to waste cost variation and their 90% confidence intervals for each design spot of Table 2. The most influential waste to total cost variation is defects (30.3%) in spot II and waiting customer (47.4%) in spot V. This implies that an engine manufacturer should focus on material waste, while a screw manufacturer should focus on the demand waste. This idea can be further explained by examining the relative cost in trade-off scenarios. Both the shortage of fasteners or engines can stop an automotive assembly line, which can incur costs to the customer far greater than the value of the product. In other words, the value of both screws and engines are the same to the customer during a shortage. However, the nature of the product, process, and/or business dictates different trade-offs. In the case of the screw supplier, the customer waste costs are relatively more important than the material or resource waste costs, while the material waste costs are relatively more important than the customer waste costs for the engine supplier. Therefore, the information about the influential wastes can be useful in making effective system design trade-off decisions.

5. Discussion

A general trend was observed in the six design spots. Wastes like defects, transportation and waiting customer are influential to total waste cost variation in almost all the design spots, and are therefore the most influential material, resource, and demand wastes, respectively. This can be explained by examining financially-dependent and independent wastes. Financially-dependent wastes are those whose cost parameters are directly calculated from other costs. For example, the inventory holding costs are calculated directly from the actual material costs and cannot be more than the material cost. On the other hand, financially independent wastes are those whose cost parameters are

Table 4: Distribution of Product Waste Cost Variation

Waste		**Percent Contribution to Spot II**				**Percent Contribution to Spot V**			
	Category	***To System***			***To Category***	***To System***			***To Category***
Demand	**Overproduction**	0.2	20.9±0.6	0.6±1.0	2.9±4.9	0.4	47.4±0.8	0.0±0.0	0.0±0.0
	Wait Customer			20.2±0.8	97.1±4.9			47.4±0.8	100.0±0.0
Material	**Defects**	0.4	37.7±1.2	30.3±0.4	80.3±1.3	0.4	32.7±0.4	26.4±0.3	80.9±0.1
	Warehouse			7.2±0.2	19.1±0.5			6.3±0.1	19.1±0.1
	WIP			0.2±0.7	0.6±1.7			0.0±0.0	0.0±0.0
Resource	**Motion**	0.4	39.5±0.5	4.1±2.1	10.4±5.2	0.2	14.2±3.1	0.7±1.8	3.6±9.9
	Transportation			*19.3±5.3*	*48.9±14.0*			*9.4±2.9*	*68.8±28.6*
	Wait Machine			*11.8±4.4*	*29.7±10.7*			*3.4±2.8*	*24.0±21.2*
	Wait Operator			4.3±2.2	10.9±5.5			0.7±1.8	3.6±9.9
Unexplained				2.7±0.0				5.7±2.7	

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Table 5: Largest Three Contributor Wastes to Total Waste Variation (Percent)

Material Ratio					
		Demand Ratio	*0.2*		
	M	Defects	***46.4 ± 1.21****		
	M	Warehouse	10.6 ± 0.49		
0.6	R	Transportation			
	R	Wait Machine			
	D	Wait Customer	18.9 ± 0.98		
		Demand Ratio	*0.4*	*0.2*	
	M	Defects	26.4 ± 0.34	***30.3 ± 0.41***	
	M	Warehouse			
0.4	R	Transportation	9.4 ± 2.93	19.3 ± 5.25	
	R	Wait Machine			
	D	Wait Customer	***47.4 ± 0.75***	20.2 ± 0.76	
		Demand Ratio	*0.6*	*0.4*	*0.2*
	M	Defects	9.2 ± 0.33	12.9 ± 0.48	
	M	Warehouse			
0.2	R	Transportation	5.9 ± 4.55	19.5 ± 6.95	***33.9 ± 9.95***
	R	Wait Machine			18.2 ± 8.55
	D	Wait Customer	***75.3 ± 1.00***	***48.6 ± 0.79***	21.2 ± 1.14
		Resource Ratio	*0.2*	*0.4*	*0.6*

*90% confidence interval

independent of other cost parameters. For example, transportation cost corresponds to the cost of the transportation resource being used and are not derived from other costs such as the value of the materials being transported. In this case, defects is a dependent waste and it uses the full cost of the material being scrapped, unlike the inventory, which only uses the fractional cost as the holding cost of the material. Therefore the possibility of defects being the most influential material waste is high. Transportation is the most influential resource waste because it has a high probability of being saturated in an efficient system. Waiting customer is the most influential demand waste because it bares the entire cost of the value added activities, whereas over-production is a dependent waste using only the fraction of the material cost. Over-production waste is diminished at high demand ratios as the material cost has to be kept lower than the customer cost in order to satisfy the PR constraints.

Figure 2 is a scatter plot of the variation in total system waste cost at various design spots. The most expensive spot is VI. Even though the average total waste cost is close to other design spots, spot VI has the potential to generate very high total waste cost due to its variance. In design spot VI, the demand ratio is 0.6 and the most influential demand waste is expensive customer waiting.

A stepwise linear regression analysis on the transformed normalized aggregated data was performed in order to understand the effect of the design spots on system waste costs. The total waste cost data was found to be lognormal and a lognormal-normal transformation was done to improve the regression fit. The fit, with significant factors at a 95% confidence level, had an adjusted R^2 of 0.95:

$$T_w = 0.27 - 0.08M_w - 0.27R_w + 0.35A + 0.44E + 0.34F + 0.32C + \varepsilon \quad (4)$$

Equation (4) includes the effect of the material and resource ratio, and finds that only defects, customer waiting, machine waiting, and motion were significant. From Equation (4) it can be understood that there is a significant difference between the design spots at 95% confidence level because the ratio coefficients are statistically significant. Earlier, waiting customer was found to be the most influential demand waste. It is seen to have the largest regression coefficient, which further supports the previous analysis as the most important system waste cost driver of the pareto-optimal lean system. Moreover, Gopinath & Freiheit (2009) found customer waiting was identified as having a high correlation with other system wastes. And as noted earlier, in trade-off situations, demand waste tends to be the system waste cost driver. The system waste cost decreases as the material and resource ratios increase. Therefore, there is savings potential in trade-off situations when systems can be designed to operate at different spots.

Analysis of Table 5 reveals that the contribution of specific wastes variation increases approximately linearly as their associated ratio increases. For example, the most influential material waste is defects and its contribution to the

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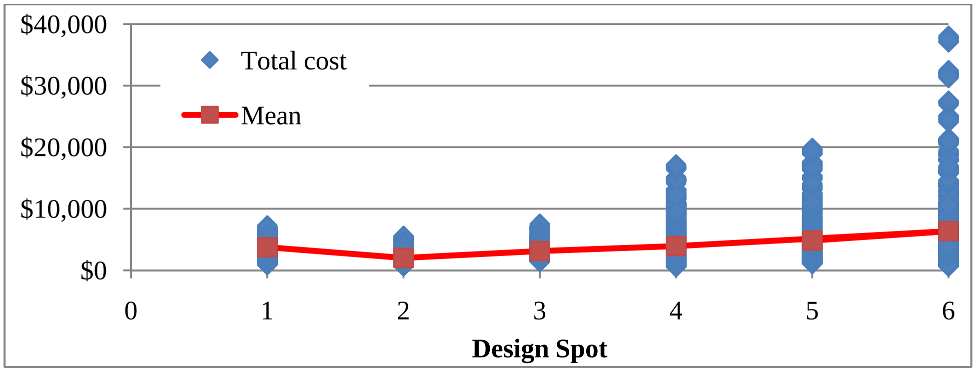

Figure 2: Total System Waste Cost at Different Design Spots

total waste variation increases approximately linearly as the material ratio increases. Similarly, transportation, the most influential resource waste's contribution increases approximately linearly as the resource ratio increases. This linear relationship can be used to roughly predict the top contributors' contribution to the total waste cost variation in other design spots while making trade-off decisions. Waiting machine and warehouse inventory can be considered as important resource and material wastes in addition to the influential transportation and defects wastes.

6. Conclusion

The behaviour of wastes in efficient, waste-dependent lean manufacturing systems has been examined in this paper. Proportional ratios have been proposed to classify different system designs in this paper. Wastes contribute to the product cost and the most influential wastes that affect product cost vary with respect to system design. The effect of different wastes on total waste cost has been examined using design of experiments and discrete-event simulation by exploiting the financial trade-off relationship between the wastes. Moreover, it is noted that the same system waste performance can be achieved at various cost parameter settings by just maintaining the ratios. Waiting customer waste cost is found to be the most influential parameter of the 'pull' system. It was found that system classification with PRs has the potential to cut systems costs where trade-off decisions can be made. In future work, it is suggested that the effect of system parameters on product waste cost be studied.

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