Evaluating the Role of Product Design and Process Time Variability in Determining a Configuration of Disassembly Stations

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ABSTRACT

The depletion of natural resources has necessitated a better management of resources. One of the methods in this regard has been the reuse of materials and parts from products at the end of their life cycles, which requires a suitable configuration of disassembly systems for an effective operation. In this paper, we compare performances of two types of system configurations: standalone tear-down-stations and disassembly lines. These system configurations are tested for the disassembly of class 8 trucks to recover parts, which are then remanufactured or refurbished for reuse. A key feature of this product, and that of a used product in general that is disassembled, is the uncertainty of the processing time of a disassembly step. This uncertainty can lead to difficulties in proper line balancing, bottlenecks, inefficient use of resources, and generally, reduced throughput. In order to overcome these limitations, in this paper, we investigate the above disassembly facility configurations, and determine how their performances are affected by variability in operation times.

1. Introduction

Product disassembly is a key activity in the value recovery process. Increasingly, the companies are looking for ways to recover value from end-of-life (EOL) products through resale, remanufacturing, or part salvage. This is driven by the profitability of value recovery activities and/or the desire to create an environmentally sustainable economy. In 1996, remanufacturing alone accounted for 0.4 percent of the U.S. economy as a $53 billion industry [1]. As of 2001, the largest amount of remanufacturing expenditures were incurred by the U.S. Department of Defense ($10 billion), followed by transportation ($8 billion) and automotive/light truck ($6 billion) [2]. These numbers do not include the economic value of other value recovery activities such as part refurbishment, resale, and salvage. Additionally, for environmental reasons, there are government mandates in some countries that require the original equipment manufacturers (OEMs) to handle the EOL of their products. For example, the European Union has enacted directives on EOL Vehicle [3] and Waste Electrical and Electronic Equipment [4]. Since most value recovery strategies require disassembly, it is important to design efficient disassembly systems.

Disassembly systems can come in many forms, from disassembly lines to craft-style project-based systems. The assembly line is a common production system and is typically associated with high throughput rates for mass production [5]. An assembly line requires expensive specialized equipment to decrease processing time and reduce processing time variance. Therefore, high production volumes are required to justify the high fixed cost of the equipment. Product disassembly, however, is characterized by: (a) highly variable product conditions, and (b) low volumes, which tend to make it a manual process that is labor intensive [6]. Thus, the disassembly process might not be best performed on stations arranged along a line. This might be particularly true for disassembling large products, such as class 8 trucks, in which multiple workers can remove parts simultaneously. In this case, standalone tear-down-stations may be more efficient.

In this paper, we specifically consider one or more standalone tear-down stations (SA-TDS) for truck disassembly. This system is characterized by SA-TDSs in which an entire product is disassembled at a SA-TDS by one or more workers removing parts simultaneously, if possible. Additionally, workers are shared among different SA-TDSs. For this paper, we assume that the workers are cross-trained, and therefore, are able to perform any task. This type of system can be applied to any product, but would tend to be most applicable in situations where production volumes are relatively low, many tasks can be worked on simultaneously, and task times are highly variable (the opposite

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conditions to those required for an assembly line). Also, a production system like this can be used to build or disassemble large products, such as ships, in which case, we can call each station as a project-based workstation (PBWS).

The objective of this paper is to investigate performances of disassembly line and SA-TDS configurations in view of: (1) different workforce levels, (2) product design, (3) processing time variability, and (4) number of SA-TDSs. In particular, our objective is to study the impact of these factors on the average and variance of system throughput resulting from these two system types. In Section 2, we present the pertinent literature in this area. Analyses of the disassembly and SA-TDS systems are provided in Section 3. Section 4 gives an example of a disassembly system design for a real-life problem. Finally, the paper is concluded in Section 5.

2. Literature Review

One type of production system used to disassemble a product is like an assembly line (and is correspondingly called a “disassembly” line) [7]. Assembly line features include, among others, (i) movement of parts on the line either simultaneously on all the stations (called synchronous line movement) or individually from one station to another as a subsequent station becomes available (called asynchronous line movement), (ii) balanced or unbalanced stations, (iii) deterministic or stochastic processing times, and (iv) existence of buffers [8]. The disassembly line for the problem on hand is a balanced asynchronous line with no buffers and stochastic process times. Analytic results for this problem have only been reported in the literature for special cases with at most 3 stations (e.g. for exponential processing times and unbalanced line [8]). As such, in general, this problem is traditionally analyzed through use of regression models based on simulation [9]. For synchronized lines with no buffer, expressions for throughput are available for iid exponentially distributed processing time and iid uniformly distributed processing times with range (2-b, b) [8].

The other production system that we consider is the multiple SA-TDS with shared workers, in which a fixed work force must be allocated to precedence-constrained jobs (parts). This system has much in common with resource constrained scheduling problems, except that the SA-TDS system has an infinite queue of projects, in which the disassembly of a subsequent product begins immediately upon the completion of the previous product. Consider the synchronous version of a SA-TDS system in which the next product may not begin processing until all the previous products have been completely disassembled. In this case, if we consider workers to be processors, precedence relationship to be partial orderings, and parts to be removed from a product as jobs, then this is a parallel machine scheduling problem with precedence constrained jobs, and stochastic processing times. The deterministic version of this problem is NP-complete [10]. However, if there are no precedence constraints and the processing times are normally distributed, then expressions for the average and standard deviation of the makespan are given in [11]. Resource constrained project scheduling is, in general, a non-trivial resource allocation problem [12]. Consequently, to overcome the complexity associated with the mathematical analysis, computer simulation has been effectively used to study the performances of such systems in the presence of stochastic processing times [11, 12, 13, and 14].

3. Analysis of Disassembly Systems

A pertinent concept to the analysis of disassembly systems is the part precedence digraph. Part precedence relationships can be defined by a digraph in which the nodes represent operations and the directed arcs represent the order in which the operations must be performed. An example precedence digraph is given Figure 1 in which operation 1 must be completed before operations 3 and 4 can begin, and operation 2 must be completed before operations 4 can begin.

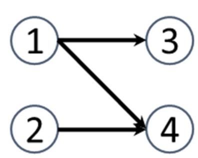

Figure 1. Example part precedence digraph.

Based on a given part precedence digraph, we can determine the maximum number of workers, P_{max}, that can perform work simultaneously at a station. Additionally, note that, at some instance during disassembly, only one worker may be able to perform work at a station (e.g. all workstations are fully manned except for one in which all the activities are completed except one). Consider the following notation:

n	Number of stations (either stations on the disassembly line or number of SA-TDSs).
m	Number of parts/operations to be disassembled from a product.
X_i, x_i	Random variable representing processing time and average processing time in minutes, respectively, to remove part $i, i = 1, \dots m$.
λ	Average throughput in units per minute.
cv	Coefficient of variation of a distribution.
CP	Critical path through a disassembly precedence digraph.
P_{max}	Maximum number of workers which can simultaneously work on a product.

3.1. Disassembly Line

Methods for analyzing disassembly line throughput are well established for both the synchronous and asynchronous cases with no buffer. The methods presented here are developed either analytically or empirically, and they are for the case of no buffer. For two-station lines, the average throughput for the synchronous and asynchronous cases is given by [8]:

$$\lambda = \frac{1}{E(max[X_1, X_2])} \quad . \tag{1}$$

From expression (1), analytic expressions for average throughput can be derived for the case of unbalanced and balanced lines with exponentially distributed processing times, and are given by [13]:

$$\lambda = \frac{X_1 X_2 (X_1 + X_2)}{{X_1}^2 + X_1 X_2 + {X_2}^2} \tag{2}$$

and [13]:

$$\lambda = \frac{2}{3x} \quad , \tag{3}$$

respectively, which hold for both the synchronous and asynchronous cases. The general expression for the average throughput of the $\boldsymbol{n}$-station synchronous line is:

$$\lambda = 1/E[max(X_1, X_2, X_3, \dots, X_n)] \quad . \tag{4}$$

From expression (4), for the special case of a balanced line with exponentially distributed processing times with mean $\boldsymbol{x}$, the average throughput is given by [8]:

$$\lambda = \left[x\left(1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}\right)\right]^{-1} \quad , \tag{5}$$

and for a balanced line with iid uniformly distributed processing times, U(2-b, b), the average throughput is given by:

$$\lambda = \frac{n + 1}{2 + b(n - 1)} \quad . \tag{6}$$

As mentioned in Section 2, it is more difficult to derive an analytical expression of throughput for asynchronous lines, in general. However, for three-station asynchronous line, if the processing times are exponential with mean processing times $\boldsymbol{x_1}$, $\boldsymbol{x_2}$, and $\boldsymbol{x_3}$ (unbalanced) or iid (balanced) uniform with coefficient of variation cv and mean processing time 1, analytic expressions of throughput are given by [14]:

$$\boldsymbol{\lambda} = \left\{\frac{1}{x_1} + \frac{1}{x_2} + \frac{1}{x_3} - \frac{(x_1+x_3)(x_1+x_2+x_3)^3}{(x_1+x_2)(x_2+x_3)[(x_1+x_3)^2(x_1+x_2+x_3)-x_1x_2x_3]}\right\}^{-1} \tag{7}$$

and [9]:

$$\boldsymbol{\lambda} = (\mathbf{1} + \mathbf{0.8037}\boldsymbol{cv})^{-\mathbf{1}} \quad , \tag{8}$$

respectively. For most other cases, simulation is used to develop expressions for average throughput. A distribution-free estimate of throughput for the balanced three-station asynchronous line if all processing times are iid with mean of 1 minute is given by [15]:

$$\boldsymbol{\lambda} = \frac{\mathbf{1} + \mathbf{0.0775}\boldsymbol{cv}}{\mathbf{1} + \mathbf{0.9125}\boldsymbol{cv}} \quad . \tag{9}$$

An estimate of throughput based on $\boldsymbol{n}$ and $\boldsymbol{cv}$ for the balanced $\boldsymbol{n}$-station asynchronous line with iid processing times with mean of $\boldsymbol{x}$ units is given by [16]:

$$\boldsymbol{\lambda} = \left(\boldsymbol{x}\left[\mathbf{1} + \frac{\mathbf{1.67}(\boldsymbol{n} - \mathbf{1})\boldsymbol{cv}}{\mathbf{1} + \boldsymbol{n} + \mathbf{0.31}\boldsymbol{cv}}\right]\right)^{-\mathbf{1}} \quad . \tag{10}$$

3.2. STANDALONE TEAR-DOWN-STATIONS

At a standalone tear-down-station, jobs are performed entirely at a workstation. If the distances between workstations are sufficiently small, workers and other resources may be shared between them. For instance, multiple workers may work simultaneously on disassembly tasks at a given workstation. Because multiple workers may be assigned to a single workstation and parts must be removed in accordance with the part precedence relationships, there is an inherent precedence-constrained sequencing problem with multiple processors (where each processor represents a worker). Even for the case of deterministic processing times, this problem has been shown to be NP-hard [10]. Therefore, expressions of throughput can be developed for special cases as we present in the next subsection. Additional insights can be gained for these systems effectively through the use of simulation models.

3.2.1. STANDALONE TEAR-DOWN-STATION-SPECIAL CASE: 1 WORKSTATION

The simplest case is that of one workstation with serial part precedence or one workstation with number of workers, $w = 1$, and its throughput is given by

$$\lambda = 1/\, E[\textstyle\sum_{i=1}^{m} X_i], \tag{11}$$

where m is the number of parts in the product. The workstation processing a product consisting of independent parts and number of workers, $w \geq m$, has throughput equivalent to that for a synchronous line with m stations since it would be dictated by the maximum among processing times at stations (see Equation 4.) However, for general part precedence with $w \geq P_{max}$, throughput is given by:

$$\lambda = 1/E[CP], \tag{12}$$

where CP is the length of the critical path of the product. We can derive an expression for the critical path in terms of the part processing time random variables as follows. Consider, for example, two parts (*i, j)* with processing times x_i and x_j.

- If part i must be removed before part j, then path length is $X_i + X_j$.
- If part i is independent of part j, then path length is $max(X_i, X_j)$.

For example, for the part precedence digraph in Figure 1, we have:

$$\lambda = 1/E[max(X_1 + X_3, max(X_1, X_2) + X_4)] \tag{13}$$

In general, depending on part precedence digraph, this expression may or may not be easy to derive analytically [11]. If $2 \leq w \leq P_{max}$, then this problem is the precedence constrained scheduling problem with multiple processors.

3.2.2. Standalone Tear-down-station -Special Case: n Workstations

The n workstation case with general part precedence is difficult to analyze in general. However, under certain conditions, the throughput can be derived analytically. First, we consider the *no idle time condition*.

Remark: If $w \leq n$, then there will be no idle workers, and the throughput is given by:

$$\lambda = \frac{n}{n\, E[\sum_{i=1}^{m} X_i]/w} = \frac{w}{E[\sum_{i=1}^{m} X_i]}. \tag{14}$$

Note that this follows from Little's Law [17], where n represents the number of products in the system and the denominator represents the average time spent by a product in the system. A lower bound on throughput for n workstations when $w \geq n \times P_{max}$ is given by $\lambda = n/E[CP]$ if the system is considered synchronous. However, if $n < w < n \times P_{max}$ then λ is difficult to determine analytically since it is dependent on resource allocation, and it is equivalent to the precedence constrained scheduling problem with multiple processors.

3.2.3. Simulation Analysis: Comparison of disassembly line and SA-TDS for up to 5 workstations

In order to study the impact of: (1) part precedence structure, (2) processing time variability, and (3) number of workers on the performance of the SA-TDSs, we used computer simulations of various system configurations. The simulation study compares the average throughput and variance of the takt time of the disassembly line with that of various numbers of SA-TDSs. The takt time is defined as$1/\lambda$, or the average inter-departure time of products in the system. Additionally, the P_{max} value of the product is varied. Specifically, we consider a product with 5 major parts. Five part disassembly dependency digraphs are considered whose P_{max} varies between 1 and 5 (see Figure 2). For each part disassembly dependency configuration, we vary the number of SA-TDS from 1 to 5.

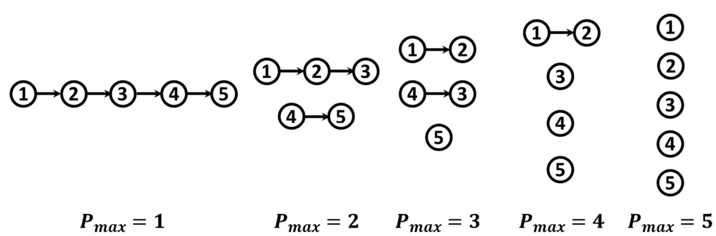

Figure 2. Precedence digraphs considered with various P_{max} values.

The impact of part precedence structure is investigated using iid part removal processing times, in minutes, with uniform distribution, U(0.5, 1.5) and the results are presented in Figures 3 and 4 for average throughput and takt time standard deviation, respectively. In general, average throughput increases both with increment in the value of P_{max} and increment in number of SA-TDSs. However, the disassembly line outperforms some SA-TDS strategies. This tends to occur for SA-TDS systems with few SA-TDSs and low P_{max}, as these systems create significant worker idle time. Takt time standard deviation tends to decrease with increment in P_{max} for SA-TDS.

Additionally, the processing time coefficient of variation was varied between 0 and 1/12 minutes while holding the mean constant at 1 minute for P_{max} values of 1, 3, and 5. Figures 5 and 6 give the average throughput and takt time standard deviation, respectively, for P_{max} of 1, 3, and 5, respectively. As expected, the disassembly line throughput decreases with increment in processing time variance for all cases. When $P_{max} = 1$, we observe that the average throughput of the SA-TDS systems is not strongly impacted by change in variance. However, for $P_{max} = 3$, notice that all of the 1, 2, 3, and 4 SA-TDS systems experience a decrement in throughput with increment in processing time variance. For the one SA-TDS case, this follows because throughput, $\lambda = 1/E[CP]$, and $E[CP]$increases with increment in variance because of the delays experienced due to the stochastic nature of processing times. For the case of 2, 3 and 4 SA-TDS, $n < w$, and so, there are instances at which workers are idle. For the 5 SA-TDS case, we observe no change in expected throughput as $n = w$ and so $\lambda = \frac{w}{E[\sum_{i=1}^{m} X_i]} = \frac{5}{5/60} = 60\ \frac{units}{hour}$. Similar observations can be made for $P_{max} = 5$. In general, note that, the takt time standard deviation increases with increment in processing time coefficient of variation.

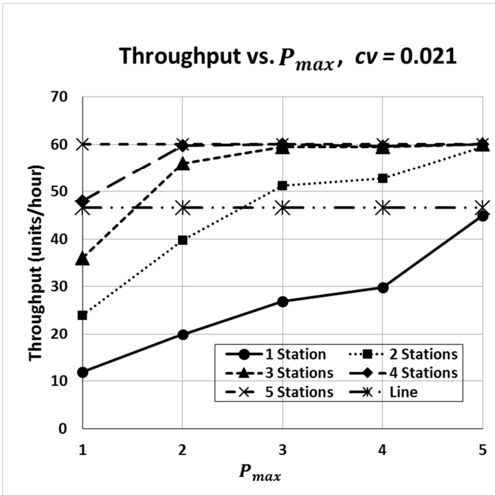

Figure 3. Average throughput vs. P_{max} for $cv = 0.021$.

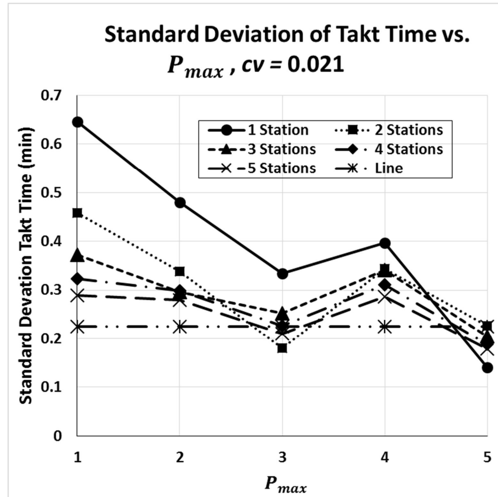

Figure 4. Standard deviation of takt time vs. P_{max} for $cv = 0.021$.

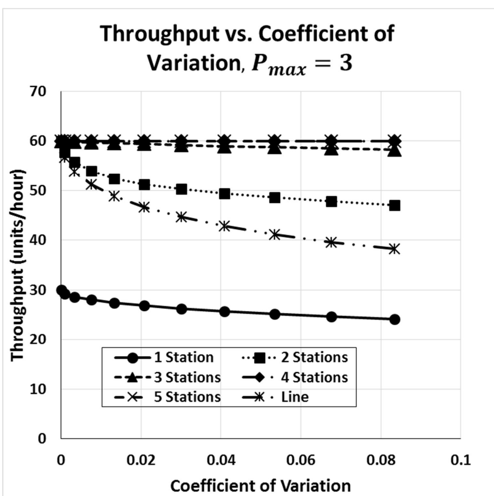

Figure 5. Average throughput vs. cv, $P_{max} = 3$.

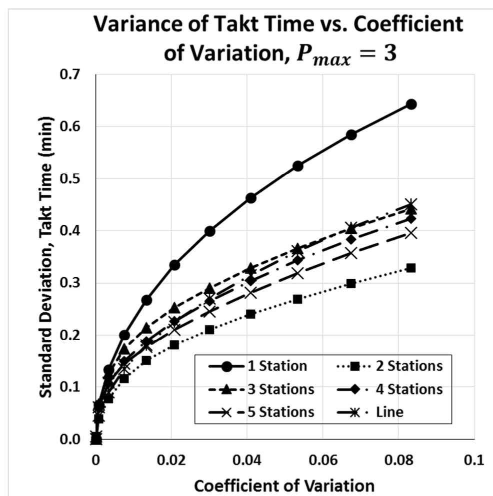

Figure 6. Standard deviation of takt time vs. $\boldsymbol{cv}$, $\boldsymbol{P_{max} = 3}$.

Finally, we investigated the impact of the number of workers. We varied the number of workers between 1 and 10 for maximum parallelism of 1, 3, and 5. Figures 7 and 8 give the average throughput and takt time standard deviation values, respectively, for P_{max} values of 1, 3, and 5, respectively. In general, we note that the gains in throughput increase linearly with each additional worker until $w = n$ because of no idle workers up to this point. Additionally, gains in throughput can be made up to the value of $w = n \times P_{max}$. For the number of workers in the range $n \leq w \leq n \times P_{max}$, the throughput is non-decreasing with increment in the number of workers. The takt time standard deviation decreases with an increment in number of workers.

4. APPLICATION

We applied the results of Section 3 to a regional Class 8 Truck dismantling company needing to substantially increase dismantling capacity. Additionally, the company required that the production system be flexible enough to handle even greater dismantling volumes in the future. In this case, the cost of labor was much greater than that of equipment and tooling. Therefore, the company wished to use as few workers as possible. The initial production system consisted of two dismantlers and one SA-TDS. The value of P_{max} in a truck is quite high; however, some dismantling tasks require two workers. Figure 9 presents a plot of the annual throughput (number of trucks dismantled) vs. number of workers employed for 3 and 4 station disassembly lines and 2 and 3 SA-TDSs.

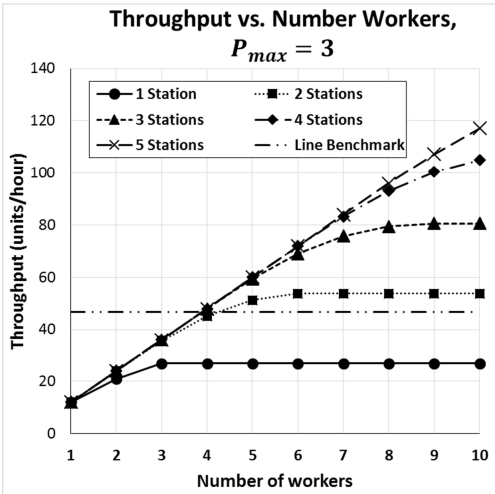

Figure 7. Average throughput vs. w, $cv = 0.021$.

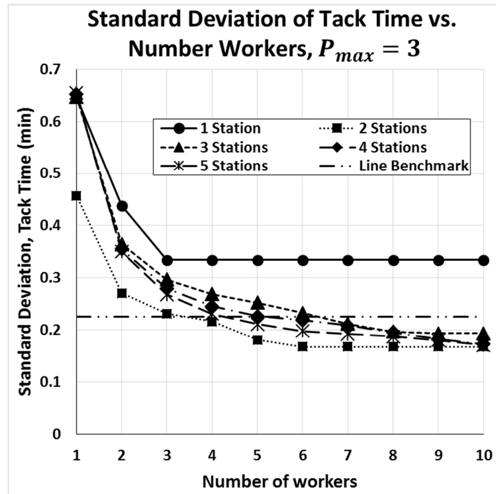

Figure 8. Standard deviation of takt time vs. w, $cv = 0.021$.

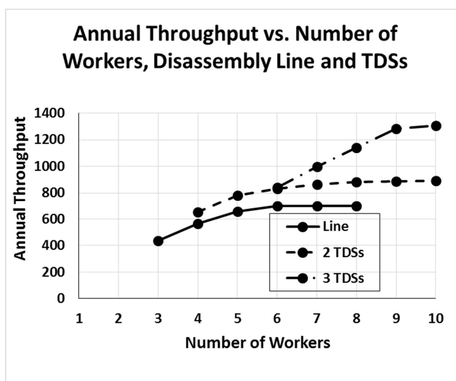

Figure 9. Annual throughput vs. $\boldsymbol{w}$ for a disassembly operation.

Consistent with our analysis in Section 3, we observe that for a given number of workers, the 2 and 3 SA-TDS strategies outperform the use of a disassembly line. Additionally, for the purposes of increasing throughput, the use of 3 SA-TDSs is the best option as substantial gains in throughput can be achieved by adding additional workers.

5. DISCUSSION AND CONCLUSIONS

In this paper, we have compared the performances of a disassembly line system and standalone tear-down-stations used for the disassembly of a product. We present results from the literature regarding the analysis of the various disassembly lines as well as our results for analyzing the SA-TDSs. Our investigation has shown that SA-TDSs can outperform a disassembly line system if the SA-TDS system is properly designed by accounting for both processing time variance and part precedence relationships. Furthermore, for companies with flexible production volumes, the SA-TDS system is a superior option since workers can be added or removed from the system without having to rebalance the system. Moreover, if the products have large P_{max} values, adding additional workers substantially improves throughput upto $w = nP_{max}$. We also successfully applied our analysis to a Class 8 Truck dismantler's disassembly system.

The SA-TDS system with shared workers might effectively be used in many situations other than that of disassemblying a large product; for example, the production of naval ships. A potential direction for future work in this area is the development of analytical expressions for estimating throughput of a SA-TDS system operating under various processing time distributions, part precedence networks, and resource availabilities.

ACKNOWLEDGEMENTS

This study was supported in part by a grant from the Transportation Equipment Manufacturers Competitiveness Initiative and by Dex Heavy Duty Parts, Floyd, Virginia

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