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A Comparison of the Manufacturing Resilience between Fixed Automation Systems and Mobile Robots in Large Structure Assembly

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Abstract

The modern manufacturing industry is undergoing major transformations due to global competition and rapidly changing market demands. Traditional systems with rigid structures are very difficult to reconfigure every time a change in production is required. A promising alternative to these is seen in mobile, self-organising manufacturing systems, where self-deploying and independent entities such as mobile robots are used to facilitate a more reconfigurable assembly process. In addition, an integral part of manufacturing is the transportation of components within the manufacturing environment. Conveyor systems are often unsuitable for moving components that are large, heavy or awkward, making them difficult to use in large structure assembly. Currently, such components are commonly transported by cranes to dedicated automation systems which are seen as expensive and unadaptable. In this paper we investigate the differences in resilience to variations between a set of mobile robots and the widely accepted fixed automation systems under different conditions. Therefore, instead of transporting components or parts to manufacturing equipment we analyse the potential benefits of transporting the equipment to the large parts. By means of simulations, the two systems are compared to one-another in scenarios of identical part arrival times and part processing capacities. Assuming equal production rates, we assess their ability to respond to (1) rush orders, (2) fluctuating arrival times and (3) production mix variations. Currently, there are no specific algorithms for process control of such mobile systems. For this reason we apply the First-In-First-Out task-selection rule. We present a comparison of resilience measures between the systems.

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Keywords: "Mobile robots; large structure assembly; manufacturing resilience"

1. Introduction

The modern manufacturing industry is undergoing major transformations due to global competition and rapidly changing market demands. Due to the ever increasing global demand for customized products, short product lifecycles and frequent market demand fluctuations, manufacturing lines are required to quickly adapt to changes in production (1). A very important measure in modern manufacturing is its resilience, it is a system's ability to mitigate or absorb the effect of a disruption and quickly recover to normal conditions (2). An integral part in manufacturing is the transportation of products within the manufacturing environment. A very common way of doing this is by means of conveyor belt systems (3). However, conveyor belts are not suitable for transportation of large, heavy or awkward products, which are common in large structure assembly. A promising alternative to this is seen in the implementation of mobile robots. Instead of transporting products between manufacturing resources, this approach therefore transports manufacturing resources between products.

Examples of employed fixed automation systems in industry include the ElectroImpact E6000 (4), HAWDE (5), GRAWDE (6) and Kuka FAUB (7). The E6000 is a drilling and riveting system that is used on aircraft wings. HAWDE is a five axis drilling machine that was also designed for aircraft wings. GRAWDE is used for drilling large holes in aircraft wings in order to be able to attach a reinforcement to it. The FAUB was designed to carry out a large proportion of riveting in Boeing 777 fuselages. All of these systems are used for high capacity work in large structure assembly.

An existing alternative for such systems is structure-mounted automation. In this approach, manufacturing equipment is manually placed on the structures where it moves and performs its tasks. Examples of this approach include the mTorres FDH (8) and ElectroImpact Flex Track (9). The FDH uses suction pads to move on structures and performs drilling. The Flex Track is a system that requires tracks to be

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positioned on the structure prior to mounting the drilling system itself. Once mounted, it can move along the tracks to the desired locations and drill holes. The disadvantages of using such systems are their speed of operation and a relatively low extent of autonomy.

A mobile robot can be thought of as a standard robotic arm, but installed on a mobile platform that adds the ability to transport itself anywhere on a shop floor. Since the recent development of industrial standard mobile robots, much research has focused on the core areas of mobile robot operation, such as navigation, localization and perception. However, no direct known work has been published on the scheduling and control of multiple mobile robots. Analogous topics may be considered to be swarm robotics (10), AGV control (11) and a few multi-agent systems (12)-(13) that have some basic transportation or scheduling considerations. In order to do that, it is important to better understand the characteristics and new opportunities when implementing mobile robots as opposed to traditional fixed automation systems with conveyor belts or cranes.

This study focuses on identifying the differences in the ability of the fixed automation systems and mobile robots to respond to the effect of occurring rush orders, fluctuating product arrival times and production mix variations in the production process.

Rush orders have been treated in literature as commonly occurring disturbances that influence the performance of a job shop (14). A rush order can be an order for a prototype, replacement order or some specific customer demand which has been placed after the production plan had already been concluded. Wu and Chen (15) and Chen (16) have produced decision-making models for the acceptance of rush orders. They assert that in order to be accepted, the gained benefit from the completion of the rush order must outweigh the negative effects of changing the current production schedule. It follows that an accepted rush order is more valuable than the regular products in a production line. Therefore in order to minimize disruption costs, it is favourable to complete the rush order and return to normal production conditions as soon as possible.

By fluctuating product arrival times we mean that there is an unsteady flow of arriving products. Production mix variations mean that the arriving products have different work capacities. Thürer, et al (17) explored the impact of different job sizes in their simulations. They state that it is challenging to release all such jobs effectively due to the differences in workload bounding and expected completion times. The allocation of workload becomes more flexible with mobile robots due to the ability to direct several manufacturing resources to the same products, provided that there are no spatial constraints.

The outcomes of this study provide an insight into the characteristics, potential benefits and issues involved with deploying mobile robots. The study serves as a foundation for a doctoral thesis where a n algorithm for self-organization of mobile robots in realistic scenarios will be developed.

2. Methodology

We apply a like-for-like approach where as many factors as possible are equal when comparing a traditional fixed automation system with a mobile robot based approach. Hence, the only major difference between the two scenarios stems from the additional freedom of movement that allows the mobile robots to concentrate around one large work piece when there is high priority set to finish the particular job as soon as possible. For this reason, the mobile robots are expected to handle the rush orders faster, return to their initial jobs sooner and cause smaller tardiness in the assembly process as a whole.

We examine the steady state of production where products arrive to manufacturing systems either at regular intervals or by probability. Identical products arrive to both systems simultaneously. When a product arrives to the workflow, the systems identify whether there are any free workstations available for it to be loaded on. Once loaded, the manufacturing systems are notified that a low priority job has become available. Manufacturing resources carry out their work according to the priority level of each product. Once a product is completed, it notifies the resources of completion and unloads itself from the workstation. During work, manufacturing resources constantly check whether any rush orders have been launched. The flow of a rush order is very similar to the flow of a regular product. The main difference is the fact that rush orders have the highest priority and the systems are required to complete the work on them as soon as possible. This means that all available mobile robots immediately halt their actions in order to complete this particular work piece and then return to continue working where they left from.

2.1 ModelSpecifications

The software package used for the simulations was NetLogo (version 5.2.1). It was set up as a job shop with a fixed automation system and mobile robots. A distributor was set up to deliver identical products to both systems at identical times. In each simulation run, the number of deployed units was matched between the systems. For example, in a simulation with 4 mobile robots (8 workstations), there were 4 units of fixed systems (also 8 workstations) to match the work capacity. The mobile robots also had a base to return to for the situations where there was no work available for them. In order to temporarily store arriving products that are unable to find an available workspace, a queue was modelled. Products in a queue constantly monitor workspaces and immediately occupy them once available. A product can also be sent to the queue if a rush order arrives and no workstation is available for it. The simulation starts with half of the workstations of each system having work pieces loaded on them.

In most of the simulation runs, the regular work pieces and rush orders require 10,000 seconds of work effort. Except for the final experiment where a mix of different products is analysed. In the mix, products with different capacities arrive to the manufacturing systems. The simulation runs have been designed to last long enough to achieve converged results, as observed in test runs.

The workstations were arranged in two rows and x columns where x is the number of deployed units of resources. Each workstation is located 60 metres away from adjacent ones. In this way, assuming 1m/s for mobile robot movement speed, it takes almost a minute for the shortest possible travel between workstations for a mobile robot.

If regular part arrival is selected, then products arrive at regular intervals so that the arriving capacity is equal to 90% of the working capacity of either system.

If fluctuating arrival is selected, then at any moment in time there is a given probability of a regular product being introduced to the work flow. The probability is set to average out at 90% of the capacity of both systems.

The rush orders arrive similarly to regular products. The arrival frequency is set as a ratio of the regular part arrival frequency. This is called the rush order to normal arrival ratio.

The measured output from the simulations is a modified version of the metrics defined by Gu, et al. (2). We measure the proportion of time that either system spends in a tardy state e.g. when a rush order has caused tardiness in regular production and the system has not recovered to its normal operating conditions yet. We also measure the time that is required for a rush order to be completed from the moment it becomes available. As the regular part arrival is set to be at 90% of the working capacity of both systems, they work at full capacity until they restore normal conditions.

2.2 Assumptions

Work capacities are equal. In order to better highlight the differences in resilience, we employ a like-for-like approach where the mobile system's work capacity is equal to that of the fixed system.

Work reliability and quality are equal. The quality of the assembly processes of either system is compliant with the requirements of the particular applications. Disruptions like maintenance, breakdowns, accidents, etc. are ignored.

Both systems take negligible time to localise. For any automated manufacturing process it is common for equipment to go through the local localisation process in order to be able to carry out work with precision. Our simulation ignores that part due to the fact that it is assumed to be of negligible value and can also be considered to be incorporated into the work capacities as described above. An advantage in favour of the fixed system in this case is the fact that mobile robots spend some time on movement between workstations.

There are two workstations per manufacturing unit. Each fixed automation system is assumed to have a large enough working envelope to be able to load products on one end of it while work is carried out on the other one. The number of workstations and deployed units for the mobile system is equal to those of the fixed system.

The mobile system is easily scalable. This is the main difference between the two approaches. When high priority rush orders are introduced to the fixed automation systems, then they are logistically unable to combine their working efforts around the same part in order to complete it faster. This simulation assumes that the products are large enough for the mobile robots to do this.

The rush order is due immediately. Both systems aim to complete the rush order as soon as possible in order to minimise its tardiness.

2.3 Control Algorithms

This section describes the control algorithms that were used by either system in this study.

Fixed system: Applying First-In-First-Out algorithm in normal circumstances. If a rush order arrives, the system immediately switches over to that until completion. Only one fixed system unit can be allocated to a rush order and therefore the remaining ones keep working on their regular products if available.

Mobile robots (non-cooperative): Each mobile robot is assigned two adjacent workstations (for analogy with the fixed system) in normal circumstances and applies the First-In-First-Out algorithm. If a rush order arrives then all the mobile robots leave their positions immediately in order to complete the rush order. If no job is available at either allocated workstation of any mobile robot, then it returns to base.

Mobile robots (cooperative): Just like the non-cooperative algorithm, but instead of returning to base, each mobile robot looks for a nearby available work piece that has been allocated to a different mobile robot. In this way, the mobile robots attempt to cooperate with others, but may lose time due to excessive travelling. They return to base only in case if there is no available work at all.

2.4 Design of Experiments

The design of experiments was set up with the following criteria:

2.4.1 Experiment 1

The purpose of this experiment was to investigate the effect of a rush order on the tardiness of either type of system and how quickly can they complete it. A plot was set up to monitor the tardiness of each system in time due to the rush order with two, three and four deployed units. The monitored values were proportional, e.g. a 20% loss of production for 2 units is the same as a 20% loss of production for 3 and 4 units. The non-cooperative algorithm was applied for the mobile robots in this experiment.

2.4.2 Experiment 2

The purpose of this experiment was to investigate how both types of systems perform under regular and irregular arrival times. Both algorithms were used for the mobile robots.

Factor	Value
Amount of deployed units	2-4
Control Algorithms	Cooperative, non-cooperative
Part Arrival	Regular, fluctuating
Rush Order to Normal Input Ratios	10-30
Sample Size	5

Table 1: The set of values for the second experiment

2.4.3 Experiment 3

The purpose of this experiment was to investigate the performance differences with product mix variation without rush orders. The capacities of work pieces arriving at either system were varied between 10 000 and 40 000 seconds of working effort.

3. Results and Discussion

In this section we present the results from our experiments and discuss the most important findings.

3.1 Experiment 1

The results for the first experiment can be seen in figure 1. In each case the tardiness increases until the rush order is completed. Each tip represents the completion of rush orders, from which point onwards the systems start recovering into normal operating conditions. The mobile robots always complete their rush orders sooner, however they also cause a larger proportion of tardiness for the regular products. This is due to allocating all available resources to the high priority rush order and neglecting the regular products. The fixed system was only able to allocate one unit per system to the rush order and therefore the rest of the units continued working on the regular (low priority) products.

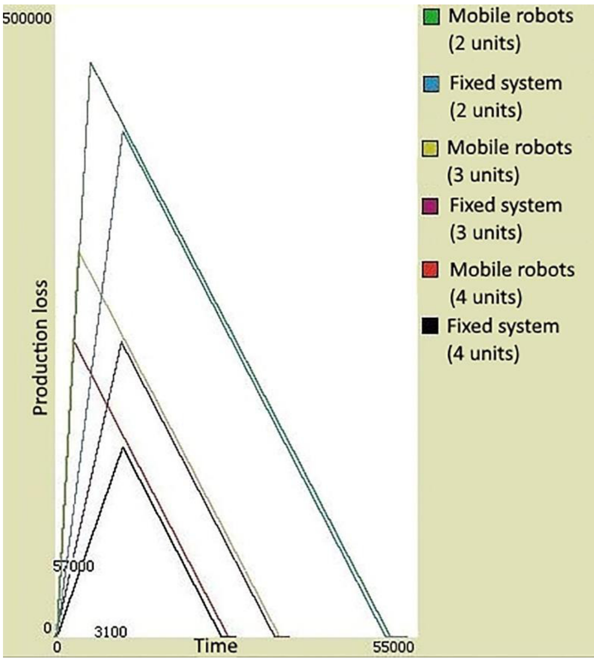

Figure 1: The effect of a rush order on the tardiness of regular products

The difference is in the mobile system's scalability that allows the workforce to be utilized where required most. Essentially, the product loss is nearly equal for both systems, however it is more intense in time for the mobile system.

This means that the extent of regular product tardiness is higher for the mobile system than it is for the fixed system at the early stages after a rush order arrival. In a realistic scenario with actual deadlines and smart operation algorithms this means that the mobile system has a much better ability to balance the workload in a favourable way. The adverse effect of the higher intensity production loss is the result of the fact that fewer workstations are freed during that time and there is a chance that some arriving products will not find available workstations. More advanced algorithms will need to take this into consideration.

The reason why the fixed systems recover slightly earlier is due to the fact that the compensation for production loss actually begins as soon as the rush order has arrived and it does not lose time due to travelling. As one unit starts working on the rush order, the rest of the units temporarily receive more than the full remaining capacity in regular products. Essentially, before the rush order arrival, both systems were working at an average of 90% efficiency. Once the rush job arrived, the mobile robots started losing 90% workload to the regular schedule due to committing full effort to the rush order. However, in case of the 4 units for example, the fixed system was only losing 15% of its workload to regular products. The reason for this is that instead of committing 90% of all available manufacturing capacity to regular products, it was now committing 75% (one unit out of four is 25%. This is how much was temporarily allocated to the rush order). For 3 units the loss was 23.333% (66.667% instead of 90%) and for 2 units it was 40% (50% instead of 90%). Both systems at each amount of units recovered at a uniform rate of 10% due to committing 100% of existing manufacturing capacity on regular products while receiving 90% of it into the job shop.

3.2 Experiment 2

The results for the second experiment are shown in figure 2 and figure 3. With regular arrival times, the results from experimental runs are consistent; however with varying arrival times, there is a large spread in results. Nevertheless, the trends are the same as with regular part arrival.

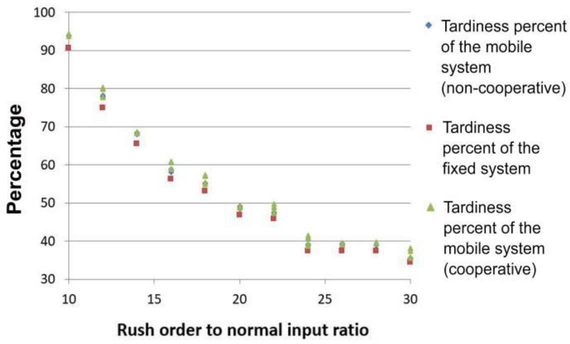

Figure 2: Comparison of each system and algorithm at regular part arrival times

An important detail is the fact that occasionally a large amount of products arrived in a very short space of time in the probabilistic case. This led to an accumulation of products in the queue. Very little can be done to avoid difficulties when arriving product capacity is greater than the manufacturing system's capacity: in such a case it is inevitable that a queue will build up.

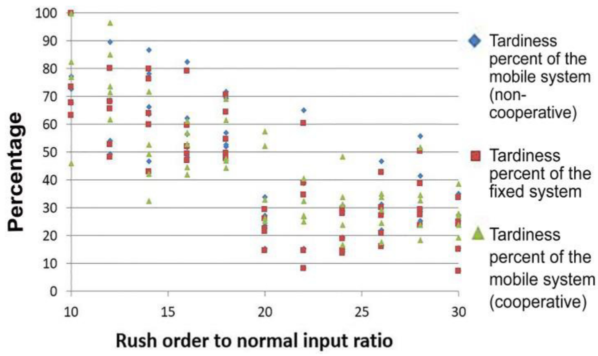

Figure 3: Comparison of each system and algorithm at fluctuating arrival times

A key indicator is the mobile system's ability to complete a rush order sooner than the fixed system. The average rush order completion time ratios (between types of systems) in percentage are shown in table 2.

Algorithm, number of deployed units and product arrival	Percentage of time to complete rush order in relation to fixed system
Non-cooperative, 4, regular	25.97 ± 0.08
Cooperative, 4, regular	25.92 ± 0.14
Non-cooperative, 4, fluctuating	25.91 ± 0.34
Cooperative, 4, fluctuating	26.16 ± 1.42
Non-cooperative, 3, regular	34.07 ± 0.06
Cooperative, 3, regular	34.10 ± 0.11
Non-cooperative, 2, regular	50.70 ± 0.07
Cooperative, 2, regular	50.72 ± 0.13

Table 2: Rush order completion time ratios between systems in percentages

At four units, the mobile robots spent slightly more than a quarter of the fixed system's times to complete identical rush orders. At three units, this was slightly more than a third and at two units slightly more than a half. The additional amount is due to the time that the mobile robots spend moving between workstations. A minor difference is also noticeable between the cooperative and non-cooperative algorithms. In the cooperative algorithm, the mobile robots often moved to distant workstations to collaborate on regular products and therefore spent additional time to attend a rush order. Occasionally, the rush order appeared closer and the travel time was shorter. This was also evident in the travel and rest time of mobile robots in both algorithms. For example, in the non-cooperative algorithm at rush order to normal input ratio of 30, regular product arrival and four units, the mobile robots spent 7.19% of time in base and 1.24% moving. These values were 0.57% and 3.41% respectively for the cooperative algorithm. The average percentage of mobile systems' time spent in tardiness in relation to the fixed systems is shown in table 3.

Algorithm, number of deployed units and product arrival	Percentage of time spent in tardiness in relation to fixed system
Non-cooperative, 4, regular	104.87 ± 0.44
Cooperative, 4, regular	105.19 ± 0.84
Non-cooperative, 4, fluctuating	106.13 ± 3.66
Cooperative, 4, fluctuating	108.14 ± 4.48
Non-cooperative, 3, regular	102.95 ± 0.24
Cooperative, 3, regular	103.62 ± 0.54
Non-cooperative, 2, regular	101.89 ± 0.27
Cooperative, 2, regular	102.24 ± 0.41

Table 3: Mobile to fixed system tardiness percentages

The difference in tardiness as shown in figure 1 is quantified in this table. In our setup, we are able to complete a rush order sooner by moving manufacturing resources. As a result of moving, the total time taken to recover from rush orders is 1.89 – 8.14% longer. For a set amount of products, the travelled distance remains the same, however if the products require a larger capacity of work then proportionally the travel time will decrease. The control algorithms applied by our mobile robots can also be refined in a way that allows to negotiate on the advantages and disadvantages of each decision and result in actions that benefit the manufacturing system's requirements most.

3.3 Experiment 3

The third experiment focused on a smaller scale. It investigated the immediate effect of scalability in a situation of steady product arrival. In this case there was an equal mix of two products: ones required 10 000 seconds and the others 40 000 seconds of working effort. The work progress in time for both systems is presented in figure 4. In this case the cooperative control algorithm was selected for the mobile robots, because the non-cooperative algorithm yielded results very similar to those of the fixed system's.

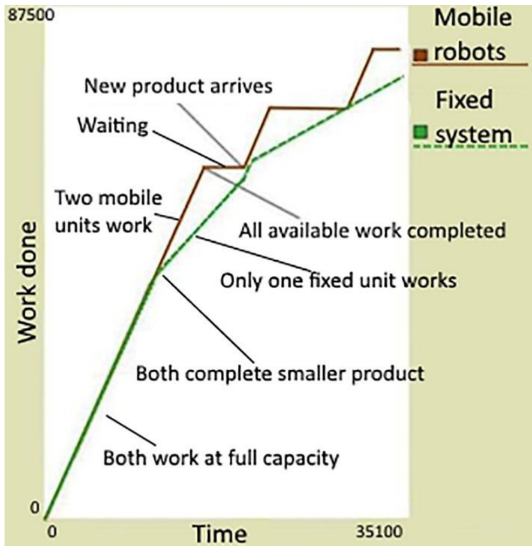

Figure 4: The work progress data of the cooperative strategy of mobile robots against the fixed system with a variable product mix

At certain instances the mobile robots operate at a higher workload than the fixed system and then temporarily stop. This is due to some of them completing their work and then proceeding to assist the ones that are still busy with products that have larger capacity. The fixed system is unable to do that and temporarily works with less active units. This difference results in some work being completed earlier by the mobile robots than the fixed systems. Other than assisting each-other, this also allows mobile robots to consider temporarily moving to a side project and be utilized there. It was observed that such gaps increase with an increase in ratios of product capacity. This finding simplifies the challenge of releasing products effectively as described by Thürer , et al (17).

4. Conclusions

The aim of this work was to investigate the resilience characteristics, potential benefits and issues associated with the deployment of mobile robots instead of fixed automation systems. A series of simulations revealed that scalability can make a substantial difference in manufacturing lines. The ability to freely distribute available workforce enables a production line to have much greater control over release times of products. The disadvantage of this is the additional non-value adding activity in the form of travelling. In our simulations, the moving between workstations added 1.89 – 8.14% to the time that was required to recover from rush orders.

Using mobile robots instead of fixed automation systems is more beneficial when the products have larger work capacity. In this case, the travel time is proportionally smaller and as a result of this, a greater proportion of time is spent on value-added activity.

Despite the shown benefits, mobile robots are still in their early stages of development. At present they cannot perform at similar performance levels (for similar amounts of capital investment) with dedicated automation systems, however it is expected that the gap will be narrowed in the near future.

The presented results were achieved with relatively basic control algorithms. Factors that commonly require consideration in real scenarios like due dates, rework/scrap and conflicting interests were not considered. In many cases the rush order would not necessarily require the full available capacity to be allocated to it. Therefore the manufacturing resources would need to be allocated in a clever way in order to better benefit the manufacturing line's requirements.

In our further work we will be developing a more sophisticated control algorithm for mobile robots. It will take advantage of the revealed benefits, minimize the negative impacts and be applicable in realistic scenarios.

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