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ABSTRACT

The manufacturing industry needs to increase productivity and flexibility to stay competitive. This requires more adaptable and versatile production capabilities. It is expected that dynamic systems, consisting of mobile robots, will be particularly prominent in manufacturing environments where it is difficult to move components and products in a flexible manner. This paper compares the relative advantages of a dynamic, mobile robot-based system with traditional dedicated automation systems. The study uses simulations to evaluate several representative scenarios with different product supply bottlenecks, interference among mobile robots and mixes of products inspired by the aerospace industry. The results show that mobility enables higher resource utilisation and increased flexibility. This highlights the potential operational advantages mobile robot-based systems would offer and gives clear justification to continue the development of dynamic, self-organising production systems based on mobile robots.

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Multi agent systems; large structure assembly; mobile robots; self-organisation

1. Introduction

In large structure assembly (LSA), there is expected to be significant potential for mobile robots to replace the dedicated large-scale automation systems that are currently in use. It is envisaged that mobile robots will allow assembly shop floors to become more responsive to product mix and volume variations compared to the current fixed infrastructure systems. Furthermore, they are expected to increase the manufacturing system's productivity, because the machines can move to available products as opposed to waiting for products to be loaded into a fixed location. This is particularly beneficial on shop floors where a crane system is a shared resource and consequently a bottleneck in the production process. By using a dynamic system consisting of mobile robots, it should be possible to increase the use of existing resources and, therefore, require a smaller manufacturing capacity to achieve the same throughput. This advantage could be used in two ways: either by reducing the capital investment in a system or by freeing up manufacturing resources to better respond to any occurring disruptions. To date, it is still unclear in which scenarios and to what extent a mobile system can outperform a dedicated, static

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manufacturing system. Hence, this paper presents the results from a systematic evaluation of these two principal systems.

The global marketplace is driving production systems to manage greater product variety and to become more responsive and agile. It is therefore not only symptomatic for LSA, but for the assembly industry as a whole (Hu et al., 2011). Mixed-model assembly systems have been shown to reduce the initial capital investment costs by enabling the production of a larger variety of products on the same line (Michalos et al., 2010; H. Wang et al., 2011). At the same time, a number of different manufacturing system paradigms such as holonic manufacturing systems (Botti & Giret, 2008), agile production systems (Elkins et al., 2004), reconfigurable assembly systems (Koren et al., 1999) and evolvable assembly systems (Onori et al., 2012) have been explored using modular plug-and-produce (PNP) combined with a multi-agent system based distributed control (Leitão, 2009). This allows automation systems to adapt more easily to changes. However, these paradigms are very focused on higher volume, highly automated systems that are still predominantly relying on dedicated conveyor-based transport systems. Reconfiguring such systems for new products or recovering them from breakdowns reveals their main disadvantage: they still require a large amount of time and effort, or redundant capabilities (Hu et al., 2008). Automated Guided Vehicles can overcome this structural inflexibility but are often not economically viable for higher volume systems, due to costly setup procedures and reduced efficiency (Beinschob et al., 2017).

In LSA, such as in the aircraft, ship, train, wind energy and many other similar industries, there is less dependence on dedicated transport systems that move assemblies between stations. Instead, due to the large size of components, they often rely on a single crane system to move products between workstations. The result is that each workstation is responsible for a much wider range of assembly steps. In aircraft assembly, for instance, a large set of drilling and riveting operations will be carried out in one workstation while the product remains fixed in that location.

For this reason, LSA relies on dedicated, expensive automation systems to increase productivity and on highly skilled manual labour to cope with the inherent variations. Due to the large sizes and complexity of the structures, manufacturing facilities require high investment, have long manufacturing lead times, and only produce relatively low volumes of products. Despite significant order backlogs,[1] it is currently very challenging to increase production rates in the aerospace sector. The reliance on dedicated jigs and fixtures, as well as highly specialised automation systems, makes it very difficult to increase productivity by incrementally upgrading production technology or reorganising production layouts. At the same time, dedicated automation systems are not always in use due to the difficulty of effectively supplying them with enough work. The supply and removal of large components to fixed location automation stations can be a major bottleneck in typical aircraft structure assembly facilities. Production layouts that require frequent, continuous or complex movement of products do not provide good answers for large products. Large jigs and fixtures reduce geometric variation but are inefficient and inhibit more agile shop floor concepts to be explored. These barriers can be overcome by using manual labour, but they do not provide the answer to addressing the underlying productivity challenges.

Mobile, versatile automation solutions based on industrial robots could provide a solution that would transform large structure assembly and significantly increase productivity, whilst simultaneously being agile enough to better cope with production volume and mix fluctuations. Giordani, et al. (Leitão, 2009), for instance, showed that employing mobile robots can make shop floors react effectively to scenarios when key resources become unexpectedly unavailable. While there are still many technical challenges to address to ensure that mobile industrial robots can achieve the same accuracy and quality standards as highly dedicated, fixed installation automation systems, this paper focuses on systematically comparing their advantage from an operational perspective. This is important to fully understand when, and, under which circumstances mobile robots will offer a more efficient and competitive solution. However, currently, without any clear benchmark information, investment in the development of such mobile systems is premature and not based on existing established operational research principles.

This paper uses a representative test case inspired by the aircraft wing assembly industry to systematically compare and analyse fixed installation automation systems with mobile robot-based systems. A set of key performance characteristics were identified to map out their respective advantages when varying a number of production parameters. The focus of this work was not to investigate a specific scenario but rather compare how both these principal systems' approaches respond to a range of different production scenarios. Clearly, it can be expected that the fixed, dedicated system will perform well for low variety, fixed volume production scenarios. What is less obvious, is at what point more agile mobile systems will start outperforming fixed automation systems.

The paper presents an overview of current aircraft assembly technology used to build the required background for the models created to analyse and compare fixed systems with mobile systems. Both, the background of assembly technology as well as a review of other related studies are given in section 2. Two formal models of aircraft inspired assembly systems, both fixed and mobile, are presented in section 3, including a set of systematic benchmarking scenarios. The results from extensive system comparison simulations are discussed in section 4 and the underlying findings are summarised in the conclusions section.

2. Background and state-of-the-art

2.1. Automation in large aircraft structure assembly

In the aerospace industry, fixed, dedicated automation systems are an established method used to carry out specific assembly processes such as drilling and riveting to build the required large structures (wings and fuselage) for long periods of time (Jefferson et al., 2015). Examples of these systems include the Kuka FAUB,[2] ElectroImpact E7000,[3] GRAWDE[4] and HAWDE.[5] These systems perform at a very high standard (high production rate, accuracy and reliability) for their intended tasks. However, they are very difficult to adapt to changing requirements. Moreover, they can be underutilised in large structure assembly, where it is very difficult to achieve a steady flow of products.

It can be observed that in the context of structural assembly, a number of mobile robot platforms are beginning to be deployed in the aerospace industry. They can generally be thought of as standard 6-axis industrial robots that have been mounted on a mobile platform to allow them to move along the large components. Some systems also include vertical lift platforms to extend the effective reach of a standard industrial robot. These mobile platforms should be re-deployable across workstations. An example of a lightweight mobile robot is the Kuka Mobile Robotic Platform (see Figure 1) and an example of a heavyweight one is ElectroImpact's mobile robot.[6]

The large, heavy and awkward to handle products are not practical to handle by means of a conveyor belt system or use local pre-process buffers that are common in the manufacture of smaller products. Instead, products are usually transported by crane systems directly to the available machines. For this reason, and due to the highly specialised nature of the machines, the shop floor is typically arranged as a process layout as opposed to a flow layout. One challenge arising from the use of crane systems is its availability. There may be only one crane for the whole shop floor area. Installing several crane systems on the same shop floor is usually not sensible, because they would cause routing issues and additional management challenges (Boysen et al., 2016). Another challenge for the effective use of machining resources is that it is often not possible to use these dedicated drilling and riveting machines while a product is being loaded or unloaded from their fixtures. The loading procedure can be very time-consuming and therefore reduce the availability of the manufacturing systems. Also, dedicated fixtures restrict the number of different product variants to be assembled on the same workstations. This introduces further scheduling constraints.

The disadvantages of mobile robot platforms in comparison to a fixed automation system are their accuracy of localisation and structural stiffness. Dedicated automation systems can be fixed firmly onto a base and use large rigid structures to achieve a very high stiffness. They can then be calibrated to achieve the necessary accuracy for a specific workstation setup. The development of more accurate industrial robots (Buschhaus, Krusemark et al., 2016b), more ubiquitous sensing technology (Buschhaus, Grünsteudel et al., 2016a) and new backlash free actuators (F. Wang et al., 2016),

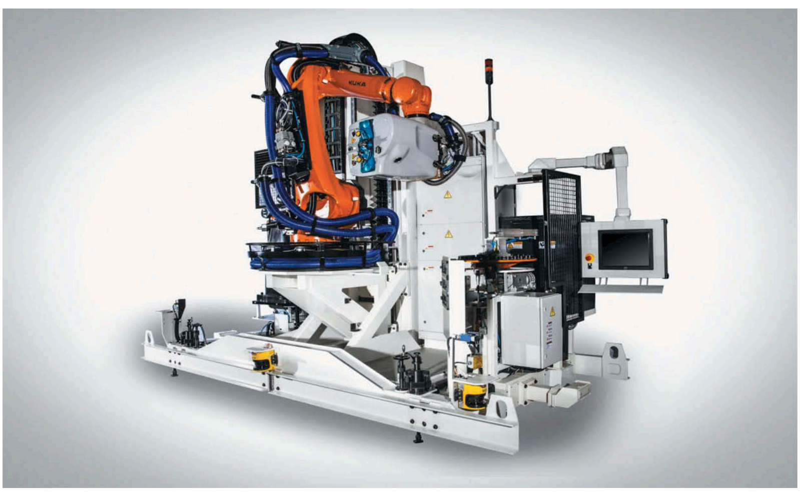

Figure 1. Mobile robotic platform and multifunctional robotic end effector are used for drilling and fastening aircraft wing assemblies (Courtesy of KUKA systems aerospace).

however, makes mobile robot platforms increasingly more accurate and capable from an automation technology perspective. This work assumes that current technical challenges will be overcome if clear operational advantages can be demonstrated. Hence, the focus of this paper is on systematically comparing the respective advantages of both fixed systems and mobile robot systems to establish a clear operational business case for either system.

2.2. Related literature

To our knowledge, the closest study to investigating the operational performance of mobile robots in factories is the work from Michalos et al. (2016). They assessed how the introduction of mobile robots to an assembly line could enhance the system's flexibility and responsiveness. They concluded that these manufacturing systems would benefit from the following advantages: higher reconfigurability, reduced duration of breakdowns, lower commissioning time, higher reliability and flexibility, minimum need for human intervention due to their autonomous behaviour and higher production variability. It must be noted, however, that they assumed that mobile robots have already overcome their current limitations, such as conflict-free path planning and accurate localisation.

Michalos et al. (2014) also implemented a method that generates a set of assignments for a mobile robot to relocate from one workstation to another. Effectively, they replaced a broken down robot by another one without human intervention. This can be considered as a step forward from the initial idea of PNP that was proposed by Arai et al. (2000). PNP was proposed as a manufacturing analogue of the 'Plug and Play' technology that had been used in computing.

To date, only the work of Giordani et al. (2013) and Ljasenko, Lohse, Justham et al. (2016b) specifically investigate decision-making models for mobile robots in manufacturing. The objective of the model in (Giordani et al., 2013) is to minimise the moving time of mobile robots in order to minimise the makespan of a set of products. The problem addressed was one where each product had already been given a predetermined number of required resources. The difference in (Ljasenko, Lohse, Justham et al. 2016b) was that the objective was to meet due times by allocating the right number of resources. The work rate on any single product could be adjusted by adding or removing resources at any time. The model was designed to minimise the total weighted tardiness (TWT) when there was a shortage of resources and to finish products early when there were more resources than necessary.

Much of the existing published literature is related to the concept of creating more dynamic, self-organising production systems based on mobile robot systems. However, only (Ljasenko, Lohse, Justham et al. 2016b) addresses the scenario where a number of resources can work on the same product to combine their work rates in order to meet due times. In other published papers, the number of resources per product has been set to one or has been non-adjustable.

There is, therefore, currently a lack of understanding of exactly what the performance differences between the two system types are in the context of large structure assembly. In (Ljasenko, Lohse, & Justham, 2016a), it was concluded that the mobile system had much greater control over product delivery times. This is because there is the ability to choose how much of the total manufacturing capacity is committed to any product at any given moment. The disadvantage of mobility is that during movement, a mobile robot is unable to do any value-adding work. The favourable factor in the case of large structure assembly is that movement is required relatively rarely and therefore it occupies a low proportion of time. Inspired by those results, a more efficient and applicable self-organisation model for mobile robots was proposed in (Ljasenko, Lohse, Justham et al. 2016b).

3. Problem formulation

The objective of this paper was to compare two principal types of manufacturing system approaches in the context of large structure assembly. The first type employs dedicated machines while the second one employs mobile robots to carry out the required processes on a range of product variants. The systems are compared to one another using the same range of production scenarios. For clear benchmarking, it was assumed that both systems are required to process the same number and type of jobs with the same working contents. One of the key differences between the two systems is that in the dedicated (fixed) automation system only one manufacturing resource (machine) can be allocated to a product at any one time whereas in the mobile system as many resources (mobile robots) as required can be allocated.

The behaviours of both fixed and mobile systems have been modelled using the multi-agent systems (MAS) approach. There are two main reasons for this; firstly, the changing environment and NP-hard nature of the underpinning scheduling problem is very time-consuming for a centralised algorithm to solve (Wan & Yuan, 2013). Secondly, mobile robots are, by their nature, suitable to act as semi-autonomous entities with limited perception and communication abilities to organise themselves. Hence, the simulation model used to compare both systems follows this approach to achieve more realistic results that also account for sub-optimal schedules resulting from distributed negotiation. In (Ljasenko et al., 2018), we presented a comparison between a partially centralised and a fully decentralised model that supports these statements.

3.1. Notations

The following notations are used throughout this paper:

C_j	completion time of processing job J_j
d_j	due time of job J_j
f	number of deployed resources of the dedicated system
IF	interference factor for the mobile system
$J = \{J_1, J_2, \ldots, J_n\}$	a set of n jobs to be processed
L_j	time required to load a job J_j to a workstation
l_j	start time of loading of a job J_j to workstation
l_j'	end time of loading of a job J_j to workstation
m	number of deployed mobile resources

(*Continued*)

(Continued).

m_j	combined manufacturing capacity of a manufacturing system's resources at job J_j
$MD = \{MD_1, MD_2, \ldots., MD_f\}$	a set of *f* dedicated resources (machines) that process jobs for the fixed automation system
$MM = \{MM_1, MM_2, \ldots., MM_m\}$	a set of *m* mobile resources (machines) that process jobs for the mobile automation system (each resource consists of two mobile robots that work in pairs)
p_j	processing time of job J_j as a function of how many resources are allocated to it
PTF	the sum of resource utilisations of the fixed system
PTM	the sum of resource utilisations of the mobile system
r_j	release time of job J_j
S_j	starting time of a job J_j
t	time
t_j	tardiness of job J_j. $t_j = C_j - d_j$, if $C_j > d_j$, otherwise $t_j = 0$.
u_j	start time of removal of job J_j from workstation
u_j'	end time of removal of job J_j from workstation
U_j	removal (unloading from workstation) time requirement of a job J_j
U	utilisation of a system. $U = \frac{PTF}{t*f}$ for the dedicated system, and $U = \frac{PTM}{t*m}$ for the mobile system
w_j	priority of a job J_j
W_j	working content of job J_j
W_A	working content of product A
W_B	working content of product B
WR_j	work rate at job J_j
$\mu_j \leq M$	a set of machines allocated to a job J_j

3.2. Fixed system model

The principal shop floor layout of the dedicated system is shown in Figure 2. The machines of the fixed automation system, MD_i, are restricted to their gantry rails. It is assumed that their rails are long enough to cover two workstations $WS_{i-1.2}$ with each machine MD_i. The total number of machines MD can be changed for different production system sizes. However, only a single machine MD_i may process a job J_j at any point in time. To be able to be processed, the

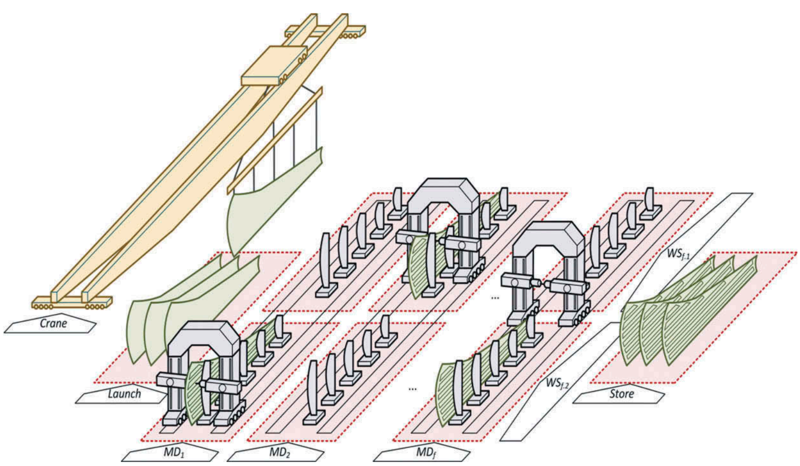

Figure 2. An illustration of the principle shop floor organisation for the traditional fixed assembly system.

job J_j must also be available on the machine MD_i's workstation $WS_{i-1.2}$. The crane system CS is able to move only one product at a time. New products are supplied from the product launch area. Looking at an individual production cycle, the crane system becomes busy from time l_j when it starts picking up a new product from the launch area and will remain busy for a duration P_j until time l_j' when the product has been loaded onto an available workstation $WS_{i-1.2}$. Once loaded, a dedicated machine MD_i, that can work in $WS_{i-1.2}$, will carry out the total work content C_j of the assigned assembly task for the job J_j starting at time S_j. The time to process a job J_j on the dedicated system is $P_j = W_j$. Once job J_j is finished on a workstation $WS_{i-1.2}$ at time C_j, it is moved to the product storage area. After F_j, the crane system CS is busy from time u_j when its starts unloading the job J_j for a duration of U_j until time u_j' when it has dropped the finished product off at the store location. The 'empty' travel time of the crane system CS between workstations $WS_{i-1.2}$ is not highlighted separately, because it was considered to be part of the whole time that it takes to load or unload a product.

A typical schedule for processing a job J_j on a dedicated machine MD_i is shown in Figure 3. It shows how the product progresses from launch until it is dropped off at the completed product storage area. The crane system CS is first busy from the moment it picks up the product at time l_j until it is loaded on an available workstation $WS_{i-1.2}$ at time l_j'. Once the job J_j is completed at time F_j, the crane system CS returns to that workstation $WS_{i-1.2}$ to unload the product and transport it to the finished product storage area. The workstation $WS_{i-1.2}$ is occupied from the moment when the loading starts at l_j until the product is unloaded from it. However, machine MD_n only becomes busy at time S_j when the job J_j has started processing on the workstation $WS_{i-1.2}$ until time F_j when it has finished. Only the time between S_j and F_j counts towards the resource utilisation. The schedule also includes repositioning times for the machine MD_i. We showed in (Ljasenko, Lohse, & Justham, 2016a) that the repositioning times of resources are negligible compared to the time required to process the jobs. The same is the case for the transport time of the CS. Therefore, for the purpose of this work, both the repositioning time for the fixed system's resources $MD_{1.f}$ and the transport time (not loading time) of the CS have been neglected.

3.3. Mobile system model

The principal shop floor layout for the dynamic system based on mobile robots is shown in Figure 4. In order to create a like-for-like comparison, the combined manufacturing

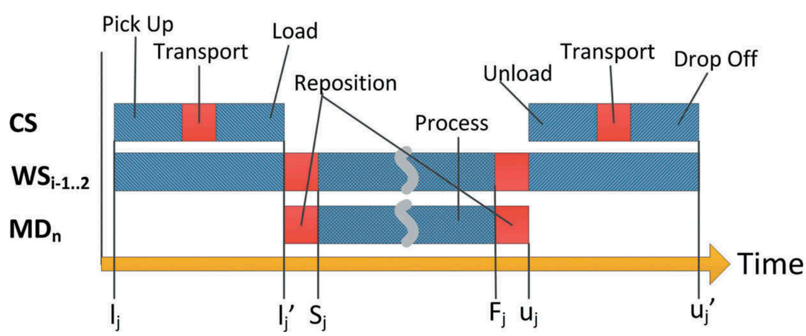

Figure 3. A typical schedule for processing a job on a dedicated machine's workstation.

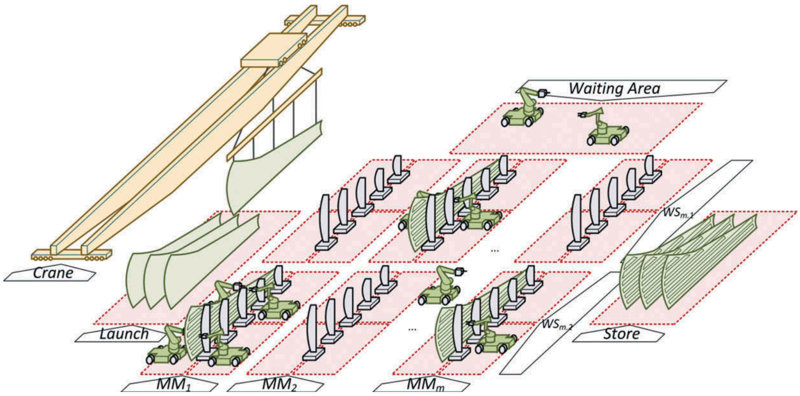

Figure 4. An illustration of the principle shop floor organisation for the mobile robot-based assembly system.

capacity of mobile resources $MM_{i.m}$ was initially equal (later adjusted to match the make spans of both systems) to that of the dedicated automation system. The number of workstations $WS_{i\text{-}1.2}$ in this layout was the same as in the dedicated system with the only difference being that there was no fixed relationship between the mobile robots and the workstations. An equivalent resource of the mobile system may be thought of as a number of smaller mobile robots that move and work together as a unit. In this work, it was assigned that two mobile robots should work together in order to process the drilling and riveting tasks. This was due to the need for supporting the opposite side of the surface when carrying out the named tasks (i.e. see the E6000 (Remley et al., 2009)).

In comparison to the dedicated automation system, the resources in this layout were able to freely move in any direction along the shop floor. In addition, it was assumed that the products were large enough that any number of resources were allowed to process the same job J_j simultaneously in order to increase the work rate R_i. The movement of jobs J_n by the crane system CS to and from workstations $WS_{i\text{-}1.2}$ followed the same procedures as defined for the dedicated system layout.

A typical schedule for processing a job by the mobile system is shown in Figure 5. The schedule was identical to the one for the dedicated system, except in this case additional machines MM_{n+1} could join and leave the job J_j as required (pre-emption). As proven in (Ljasenko, Lohse, & Justham, 2016a), this additional ability enabled the manufacturing system to better control the product delivery times. Furthermore, the moving times for the mobile system have not been neglected due to the additional need for routing and localising in a realistic scenario. The specifics of this are described in section 4.3.

3.4. Problem definition

The scheduling problem considered in this paper did not consider task sequences nor different skill sets for jobs. It was based on products that have very large work contents of the same task i.e. many holes need to be drilled and riveted on a large airframe component. The only considered sequence constraint was that each job J_j must be loaded on a workstation $WS_{i\text{-}1.2}$ before processing by machines $MM_{i.m}$ or $MD_{i.f}$ could start, and

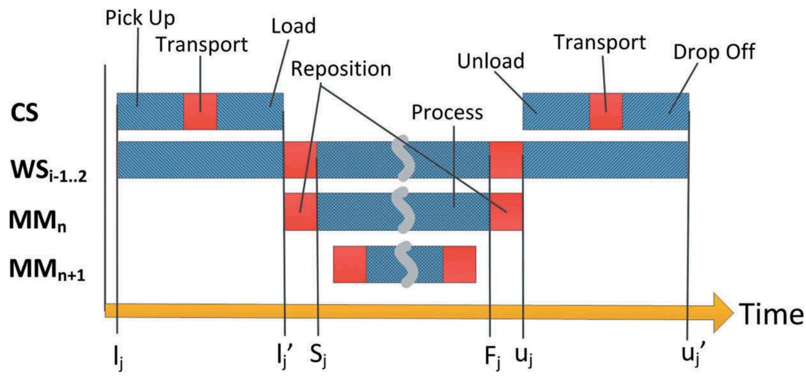

Figure 5. A typical schedule for processing a job on mobile machines.

unloaded after processing was finished at time F_j. A finite set of jobs J were to be processed by a finite set of machines $MD_{i.f}$ *or* $MM_{i.m}$ in no predefined order. Different jobs from the set J were prioritised by the fixed and mobile systems as described in sections 4.5 and 4.6 respectively.

The problem can be classified as an open shop problem with pre-emption. The objective was to minimise the makespan and by implication maximise the utilisation. Hence the objective function can be presented as shown in Equation 1:

$$\boldsymbol{O}|\boldsymbol{prmp}|\boldsymbol{C_{max}} \quad \text{(Equation1)}$$

In equation 1, ***O*** represents that the scheduling problem was considered an open shop problem. The problem was classified as such because the jobs J are launched on workstations $WS_{i\text{-}1.2}$ in an arbitrary order and the attention was paid to the processing times, throughput and utilisation of the compared systems. ***Prmp*** represents that, in this approach, the tasks were pre-emptive, meaning that they could be paused for any amount of time without any penalty. $\boldsymbol{C_{max}}$ stands for the objective of minimising the makespan and hence maximising the utilisation of the systems.

The model is subject to the following constraints:

$$s_j \geq 0, l_j \geq 0, u_j \geq 0, l_j' \geq 0, u_j' \geq 0, \forall j \in J \quad (1)$$

$$|r_{jmin}'| = L_j + p_j + p_j + U_j, \forall j \in J \quad (2)$$

$$Sj \geq lj' \, \forall \, j \in J \quad (3)$$

$$Cj = Sj + Pj \, \forall \, j \in J \quad (4)$$

$$uj \geq Cj \, \forall \, j \in J \quad (5)$$

$$mj \; max = 1 + Y(MMm - 1) \quad (6)$$

$$m = f = 4 \quad (7)$$

$$(lj, lj') =]uj, uj'[, (lj, lj') =]lj + 1, lj + 1'[\forall j \in J \quad (8)$$

$$(uj, uj') =]lj, lj'[, (uj, uj') =]uj + 1, uj + 1'[\forall j \in J \quad (9)$$

Where:

$$Y = \left\{ \begin{array}{c} 0, \textit{for fixed system} \\ 1, \textit{for mobile system} \end{array} \right\}$$

The first constraint (1) ensured that the starting times (S_j, l_j, u_j, l_j', u_j') of any activity cannot start before the simulation. The second constraint (2) specified that the minimum duration of every job $|r_j{'}_{min}|$ was the sum of the time taken to load (L_j), process (p_j) and unload (U_j) a job J_j. Constraint (3) defined that a job could only start being processed at time S_j after it had finished loading at time l_j'. The completion time C_j in constraint (4) was the sum of the starting time S_j added to the processing time P_j for each job J_j. Under constraint (5), for each job J_j, the unloading could be started at time u_j only as soon as the processing on that product had been finished at time C_j. Constraint (6) ensured that the maximum number of resources $r_{j\ max}$ that could be allocated to processing a single job J_j is 1 for the fixed system and *m* for the mobile system. The deployed number of resources (and hence the maximum values for the set of MD_f and MM_m respectively) were set to 4 under constraint (7). The crane's availability was defined under constraint (8). It established that between the start l_j and finish l_j' of loading job J_j, there could be no unloading (u_j, u_j') or loading of other jobs (l_{j+1}, $l_{j+1'}$) and vice-versa under constraint (9).

It was defined that the working capacity of each mobile resource MM_i was equal to that of a machine MD_i in the dedicated automation system model. This meant that if only one mobile resource (a pair of mobile robots) MM_i was processing a job J_j, the production rate at this workstation $WS_{i-1.2}$ was equal to the rate at a workstation $WS_{i-1.2}$ with a single machine MD_i of the dedicated (fixed) system.

4. Experimentation method

In this section, the details of the experiments are specified. Two key variables, their experimental setup and their purpose are introduced. The simulation model used for the experiment, its parameters and assumptions are then described. To conclude, a description of how the compared system types behave within the simulation is presented.

4.1. Experimental setup

This work had two objectives: i) to evaluate how much the utilisation of both systems is affected due to the bottleneck of having a single crane system (*CS)* and interfering machines (*IF*), and ii) to analyse how the distribution of manufacturing resources affects the ability to deliver products on time. This was done by introducing a product mix where product types A and B have different working contents.

Due to the nature of these systems, there cannot be an absolute comparison, rather it must be dependent on relative properties. As such, two key factors have been introduced to investigate the most likely differences between the two systems under varying technical and operational considerations.

The first one, R, is a measure of the crane system's speed of supplying products in relation to how quickly the machines can process them. The formulae for obtaining this ratio for the fixed and mobile system types are shown in Equation 2 and Equation 3 respectively. It is measured through the relative time it takes the crane *CS* to load and unload a product in relation to the average working content W_j of job J_j that the reference machine requires to complete.

$$R = \frac{\left(\overline{L_j} + \overline{U_j}\right) * \boldsymbol{f}}{\overline{W_j}} \quad \text{(Equation 2)}$$

$$R = \frac{\left(\overline{L_j} + \overline{U_j}\right) * \boldsymbol{m}}{\overline{W_j}} \quad \text{(Equation 3)}$$

Therefore, an increase in loading and unloading times (L_j and U_j respectively) or scaling up the number of machines in either system, causes R to increase, similarly an increase in product working contents W_j cause R to decrease. It can be calculated that if supplying each resource with a job and unloading it afterwards takes more time than processing the average job p_j, then R > 1 and the *CS* is a bottleneck in the production process. Conversely, if L_j and U_j are low in comparison to the average working content of products W_j, the *CS* is able to supply jobs *J* to machines faster than they get processed. This occurs when R < 1.

The second factor was the interference factor *IF*. This was required because enabling many mobile resources $MM_{1.m}$ to process the same job J_j may cause them to interfere with one another due to a lack of space. Each additional mobile resource MM_i (after the first one) reduced the individual work rates at the same product by this factor when it was applied. This is shown in Equation 4.

$$\boldsymbol{WR_j} = (\boldsymbol{1} - \boldsymbol{IF})^{\mu_j - \boldsymbol{1}} \times \mu_j \quad \text{(Equation 4)}$$

The work rate WR_j on any job J_j gets penalised by the interference factor with each consecutive mobile resource joining the product. For example, if *IF* = 0.1, the individual work rate of each RA would be 1 at $\mu j = 1$, 0.9 at $\mu j = 2$, 0.81 at $\mu j = 3$ and so forth. This representation was chosen as each added RA caused additional interference around the same PA and consequently reduced the work rate further by a set amount.

The first experiment considered identical products at different values of R and *IF*. This helped to quantify the effect the crane has when becoming an increasing product supply bottleneck (R) and the adverse effect from increased levels of interference between mobile robots (*IF*).

In the second experiment, product types A and B had their own loading and unloading times; and different working contents W_j. Two different products were chosen to investigate the effect of nonhomogeneous product supply times to workstations in both systems. Hypothetically, if a shorter and a longer work content product has the same time between loaded l_j' and due times d_j, both manufacturing systems should finish the shorter jobs first. The point of interest in this experiment was to show how much faster the mobile system can finish the longer jobs as a result of being able to add freed up resource from shorter jobs to longer ones. The due times d_j were set for each job J_j to be the average of the working content $\overline{Wj}$. Consequently, the dedicated system was guaranteed to be tardy with jobs J, where the working contents $W_j > \overline{W_j}$. This was not necessarily the case for the mobile system, because it was able to scale up the work rate if there were available resources, MM_i, to do so.

In both of the experiments, all jobs J in the launch queue were loaded in a random order. Each simulation run was finished as soon as all the products had been fully processed.

4.1.1. Experiment 1

In order to achieve the first objective, the simulation runs were carried out with different loading and unloading times but with the same working contents for all products. The percentage utilisation of both systems was extracted as the output.

The experimental settings for the first experiment are shown in Table 1. The experimental variables were the ratio R and the interference factor *IF*. The ratio R was incrementally increased from 0.4 to 4. Knowing that the *CS* would become a bottleneck when $R > 1$, it was important to range the values with several iterations from both sides. The *IF* was ranged from 0 (no interference at all) to 0.4, where each consecutive mobile resource slowed down the rest of the resources at that job by more than a third. To minimise the effect of the initial system run up and final run down, long simulation runs of 100 products with a total working content of over 5.5 hours were analysed. The experiment was split into two scenarios: i) when the *CS* was a bottleneck, and ii) when the *CS* was not constraining production throughput and scaling up the production rate resulted in an effectiveness penalty due to interfering machines.

4.1.2. Experiment 2

The second objective was to quantify the effect of the product mix at different R values. Hence, a product mix consisting of two products (A and B) has been defined. To achieve a comparable mix, the working content for product A was set at a constant 10,000 seconds of working effort, while that of product B was used to change the relative proportions. The difference in the ratio between the work contents for product A compared to product B affected the tardiness of the systems differently, depending on the R values. The due times of all products were set to the average value of the working contents of both products following their loaded times $\left(Dj = lj' + \overline{W}j\right)$. This created a scenario where all products must flow at a steady rate through a shop floor. This was to consider that, regardless of their properties, each product occupied a full workstation. If a job J_j exceeded its job due time $(Fj > Dj)$, it was penalised by one penalty point per time step,

Table 1. The experimental setup for the first experiment.

Factor	Value
Working Content of Both Products (s)	20 000
Quantity of Products	100
R	0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.4, 3, 4
Interference Factors *IF*	0, 0.03, 0.07, 0.1, 0.15, 0.2, 0.3, 0.4
Number of Manufacturing Resources per System	4
Sample Size	1

meaning that the tardiness penalty was equal for all products. The experimental setup for this experiment is shown in Table 2.

4.2. The simulation model

The comparison of the two principle shop floor layouts was carried out by means of agent-based simulations using the NetLogo 5.3.1 software package (Wilensky, 2016). Each resource (fixed machine, pair of mobile robots, and crane) was modelled as a separate agent. Due to the stochastic nature of product arrival times and product mix distributions, both systems were simulated using a Monte-Carlo approach.

The simulation model follows the flowchart shown in Figure 6. Each simulation run started with half the workstations (one for each resource) loaded with jobs. The simulation then proceeded in time steps (seconds) until all jobs were fully processed. At each time step, the resources of both manufacturing systems (MM_m and MD_f) and the crane system (*CS*) applied their decision-making policies to move, work or wait as appropriate. The behaviour model for the *CS* is described below and for the fixed and mobile manufacturing systems in sections 4.5 and 4.6 respectively.

Table 2. The experimental setup for the second experiment.

Factor	Value
Working Content of Product A	10,000
Working Contents of Product B	2,000: 4,000: ...: 18,000: 20,000
R	0.8, 0.96, 1, 1.04, 1.12, 1.4, 2, 3
The quantity of Each Product	50
Number of Manufacturing Resources per System	4
Sample Size	5

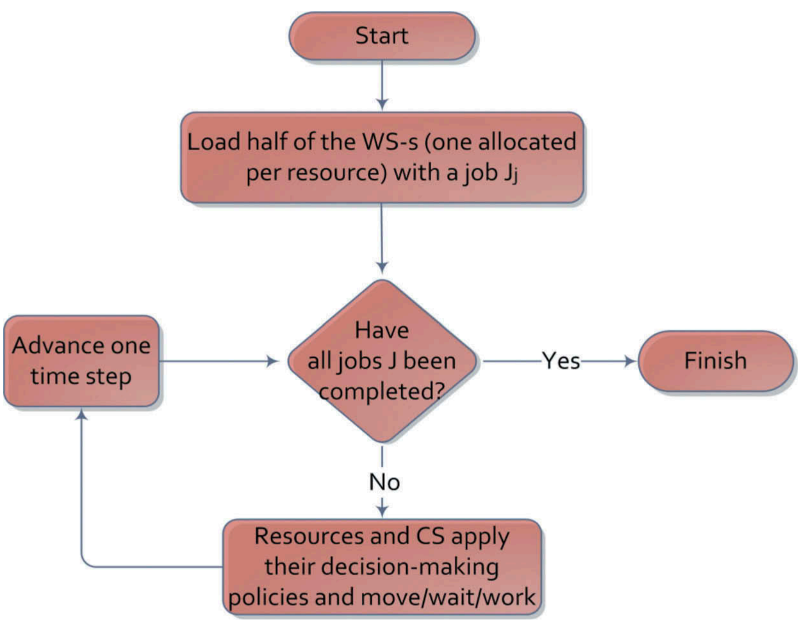

Figure 6. The general flowchart for the experiments.

The order of products in the product queue was randomised for each simulation. The crane system *CS* picked them up one by one and loaded them onto available workstations $WS_{i\text{-}1.2}$. When loading or unloading any product, the *CS* was fully occupied by this task for its whole duration. The *CS*'s decision-making logic for loading or unloading is shown in Figure 7. The *CS* prioritised loading jobs *J* (if available) to workstations $WS_{i\text{-}1.2}$, in particular to those that have waiting machines. If loading was not possible for any reason, the *CS* considered unloading completed jobs *J* if any were ready. The *CS* was not allowed to pause any operations in progress, meaning that it was committed to any task once started.

4.3. Simulation model's parameters

The simulation model's parameters ensure that the results were comparable and valid. A key part of any shop floor simulation is its geometrical layout. The layout for this model is shown in Figure 8. The workstations $WS_{i\text{-}1.2}$ were arranged in 2 rows and 4 columns, with 60m between adjacent workstations. The two workstations $WS_{i\text{-}1.2}$ in each column were allocated to the same resources ($MM_{i.m}$ or $MD_{i.f}$). The waiting area was situated 40m north from the midpoint of the northern row. To analyse a shop floor with multiple machines, four deployed manufacturing resources per system type were chosen to be a sensible amount.

The moving time for the fixed system has been neglected due to the advantages of the gantry rails. The mobile robots were set to move at 1 metre per time step. Effectively, the localisation times of the mobile robots were cancelled out by the negation of the fixed system's moving times for simplification of the model.

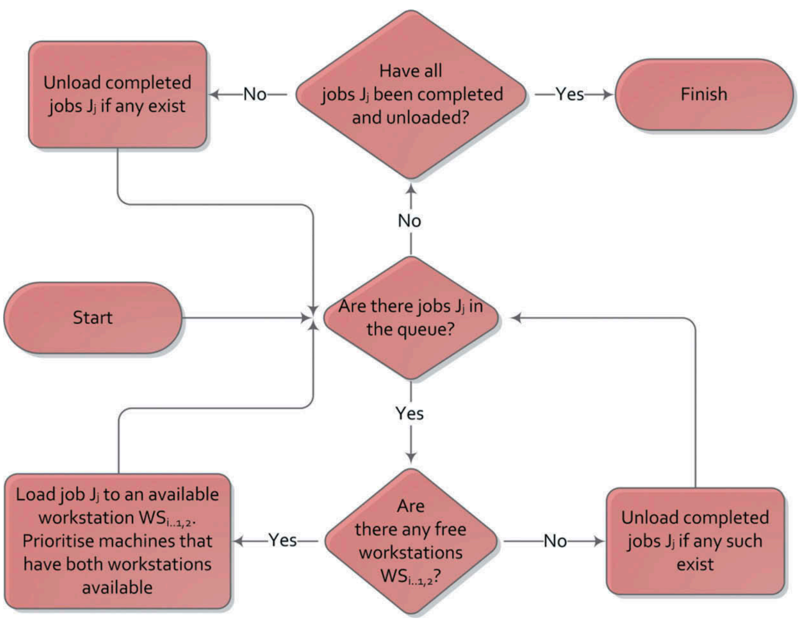

Figure 7. The flowchart for the crane's behaviour.

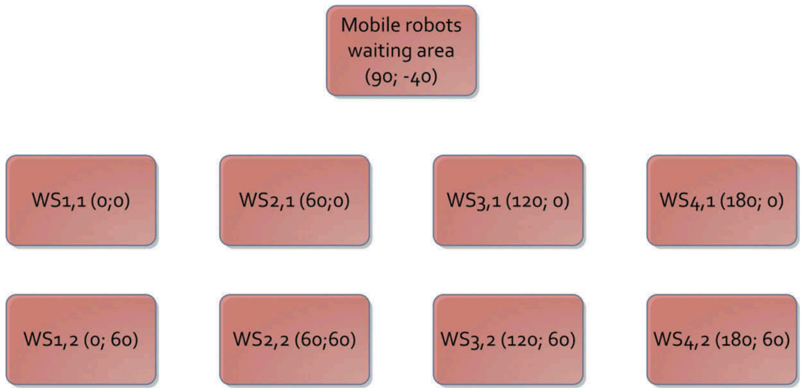

Figure 8. The shop floor layout.

The mobile resources MM_m moved in a straight line and were close enough to start work once they were within 1 m of the workstation's coordinates. A unit of a product's working content was satisfied when a unit of either the fixed or mobile system's resource worked on it for one time step.

The performance of both systems was assessed based on their utilisation t_U. The utilisation t_U was measured as a percentage of the time t that either system's resources spent processing a job J_j. It was calculated as follows:

(1) For each resource $MD_{i.f}$ and $MM_{i.m}$ per time step that they worked, a point was added to the systems' utilisation points, PTF and PTM, respectively.
(2) As a result of 1), the utilisation in percentage can be counted as:

$t_{UF} = \frac{PTF}{f*t} * 100\%$, for the dedicated system, and (Equation 5)

$t_{UM} = \frac{PTM}{m*t} * 100\%$, for the mobile system (Equation 6)

4.4. Assumptions

Work quality and reliability are equal. The quality of the assembly processes of either system was compliant with the requirements of the particular applications. Disruptions such as maintenance, breakdowns or accidents, have not been considered.

Both systems take negligible time to set up for each new product. For any automated manufacturing process, it is common for machines to go through localisation procedures when arriving products have been moved into the machines' working envelope or vice versa. Typically, both fixed and mobile systems need to reference themselves relative to key features of the products to compensate for product and fixture variations. However, given the long process times, the time required for setup is negligible. For example, the ElectroImpact E6000 (Remley et al., 2009) requires more than a week to process the wing panel of an Airbus A380 aircraft (over 100,000 holes) at its nominal rate of 16 holes per minute. Therefore, spending several minutes for repeatedly localising is of negligible time consumption in the big picture.

Relocation times for the fixed system are not significant. Due to its dedicated nature, the fixed system was assumed to be capable of moving comparatively faster between its two workstations. It has therefore been assumed that the movement time could be incorporated into the work capacity of the system. Unlike the fixed system, mobile robots need to spend more time when moving from one workstation to another. Hence, their movement times cannot be ignored especially since they act as a penalty for frequent repositioning of mobile robots.

4.5. The fixed automation system's behaviour

The flowchart for the fixed automation system's behaviour is shown in Figure 9. Its behaviour is based on the First-In-First-Out decision-making policy because the emphasis here is on comparing the system types and not to evaluate the efficiencies of the behaviour models. Hence, the agents were modelled to be all-knowing. This means that each entity has global knowledge at all times without the need to communicate with others. Once a machine MD_i has decided to start processing a product, it continues to do so until completion. It is then able to check whether a new product has been loaded to its' other allocated workstation $WS_{i\text{-}1.2}$ and the behaviour repeats until the final product has been completed.

4.6. The mobile system's behaviour

The flowchart for the mobile system's behaviour is shown in Figure 10. As with the fixed automation system, the mobile system employs the First-In-First-Out decision-making policy. The mobility of the system causes two main differences: firstly, the resources are not restricted to their own allocated workstations, meaning that several mobile robots can work on the same products; and secondly, they are able to return to the waiting area if there happens to be no available work. Therefore, the decision-making policy of each mobile resource MM_i causes them to prioritise jobs J that have been loaded to their own allocated workstations $WS_{i\text{-}1.2}$. If no work is available on their allocated workstations $WS_{i\text{-}1.2}$, each mobile resource MM_i looks for available jobs J on other workstations $WS_{i\text{-}1.2}$. Multiple mobile resources $MM_{1.m}$ are allowed to process the same job J_j at the

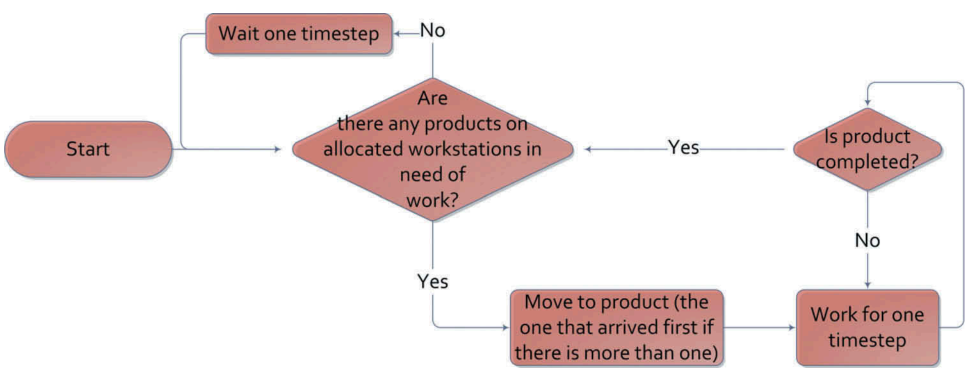

Figure 9. The behaviour model for the fixed automation system.

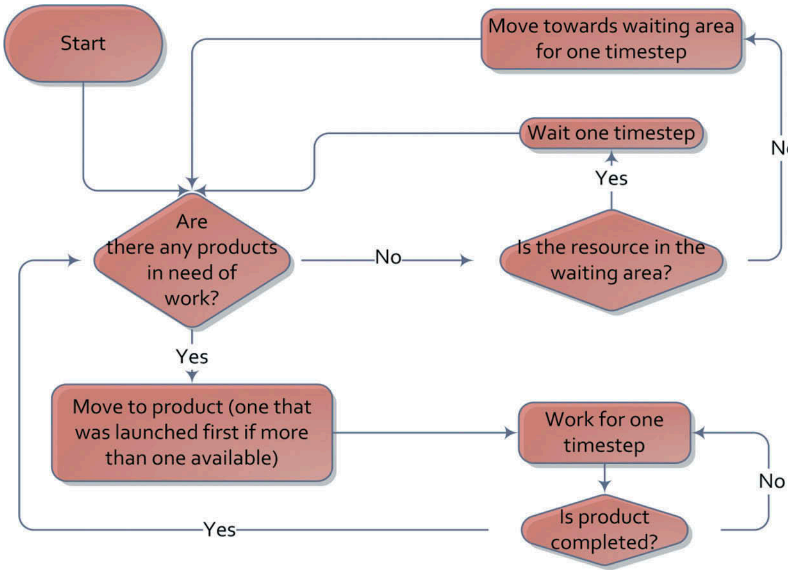

Figure 10. The flowchart for the mobile system's behaviour.

same time. If work happened to be completely unavailable at any time, the mobile resources MM_m moved to the waiting area.

5. Results and discussion

The results of the first experiment are shown in Figure 11. The plot contains the utilisation percentages for both systems and how much the mobile system's manufacturing capacity can be reduced to maintain an equal throughput with the fixed system at all considered R values. For R values of up to 1, the *CS* supplies jobs faster than either system can process. In such circumstances, the fixed system achieves a ~ 0.3% higher utilisation on average due to the advantage of more efficient movement (as described under the assumptions). For R values larger than 1, the supply of jobs becomes a bottleneck, resulting in reduced utilisation rates for both systems. This is where the key difference between the systems start to become apparent. Under these conditions, the mobile system was able to combine the work rates of several resources and complete jobs earlier. It is shown that the advantages of the mobile system increase with an increasing product supply bottleneck. The plot also shows how much the manufacturing capacity of the mobile system (at different *IF* values) can be reduced to maintain an equal throughput with the fixed system. For example, at $IF = 0.1$ and $R = 2$, the product supply bottleneck was so strong that despite the given interaction factor, the mobile system's capacity could be reduced by almost 30% to maintain an equal throughput with the dedicated system. In this case, a manufacturer would be able to reduce the initial capital investment by buying fewer mobile robots, using the time for maintenance or utilising them elsewhere. Certainly, on a shop floor with 4 dedicated automation machines, this also meant that one full unit (25%) may be reduced as well. However, in a climate of frequent and unpredictable fluctuations, this may not necessarily be wise to do. For mobile robots, the

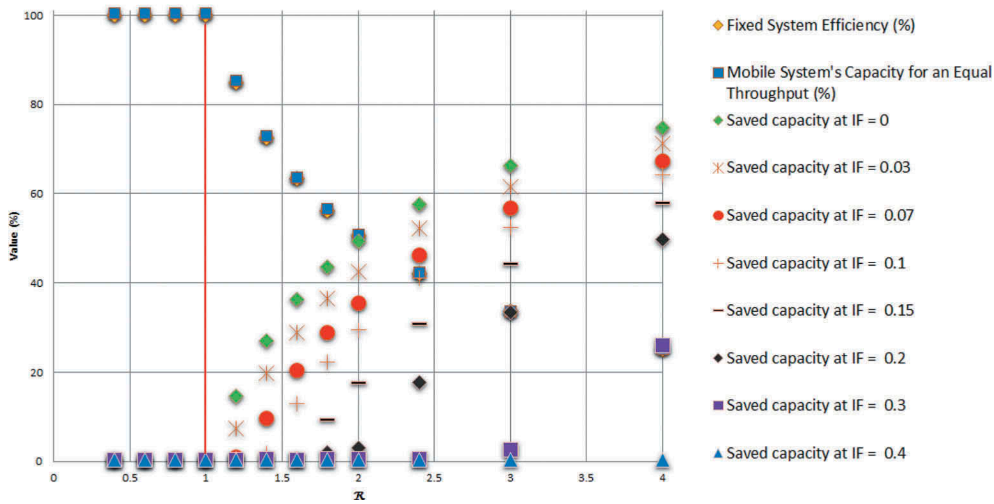

Figure 11. The results for the first experiment.

reduction is easier to facilitate on an actual shop floor, because they may easily be reallocated. This means that any decision to change the manufacturing capacity at any part of the shop floor is reversible. Whereas, for dedicated fixed automation systems, such an option is not practical, as it is difficult to reconfigure them for other tasks and their repositioning is also much more complicated.

As the *IF* increases, the benefit of using mobile robots reduces. In addition to that, the lowest R value from which the benefit of reduction begins increases as well. The results show that the mobile system has strong advantages in scenarios of product supply bottleneck and only minor disadvantages otherwise. As the behaviour model of the mobile robots in this paper is not optimising the global schedule, it is evident that there is room for further improvement of the generated results in favour of the mobile system. More sophisticated agent decision policies are expected to significantly improve the scheduling efficiency of the mobile robot system by taking into account the interference factors and considering forward planning.

The results of the second experiment are shown in Figures 12 and 13. The system with the lowest results is the least penalised system in each of the shown scenarios. Under *R = 0.8*, for example, the mobile system gains many more penalty points than the fixed system. As the manufacturing capacities were equal, the reasons for the penalty was firstly the additional movement time and secondly the inefficiency in the decision-making. The penalty points increased for both systems with an increasing product B to product A ratio simply because there was more working content to process and therefore the makespan was greater as a whole. The lack of decision-making in the mobile system was another reason why there was a need for a more sophisticated behaviour model for the mobile system. For R = 1.04, the penalty points were nearly even for both systems. As the *CS* bottleneck intensified at higher R values, the mobile system accumulated lower penalty points than the fixed system. In particular, the greatest differences were seen where the working content ratio between products was greatest. The fixed system was penalised least in cases where the difference between product working capacities was smallest.

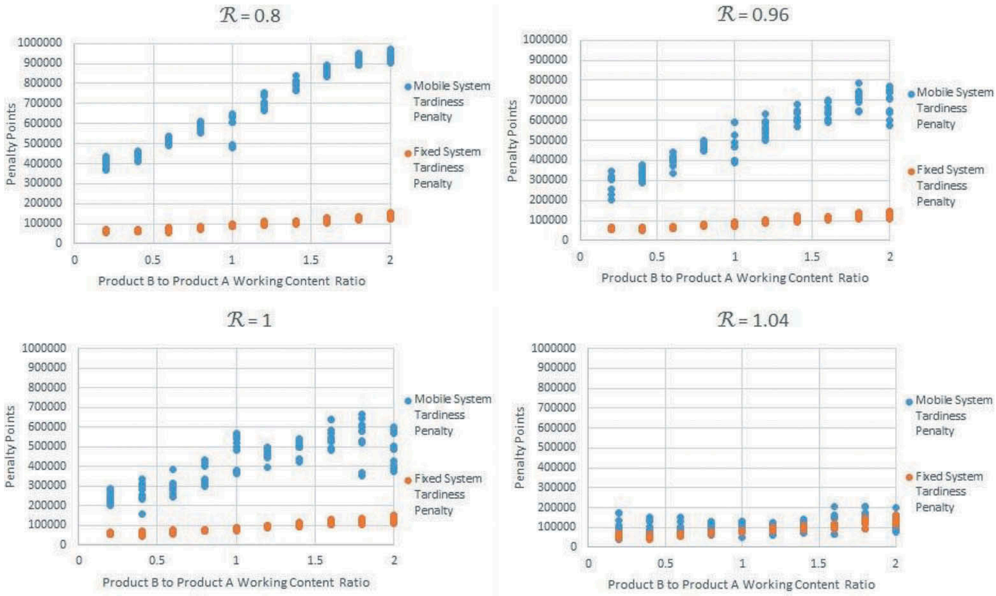

Figure 12. The results for the second experiment (1/2).

The main accumulator of penalty points for the mobile system was the inability of the control model to plan forward. Most certainly, forward-planning control models that can achieve optimal solutions with respect to their given objectives (like the one proposed in (Ljasenko, Lohse, Justham et al. 2016b) can dramatically improve the results in both experiments for the mobile system.

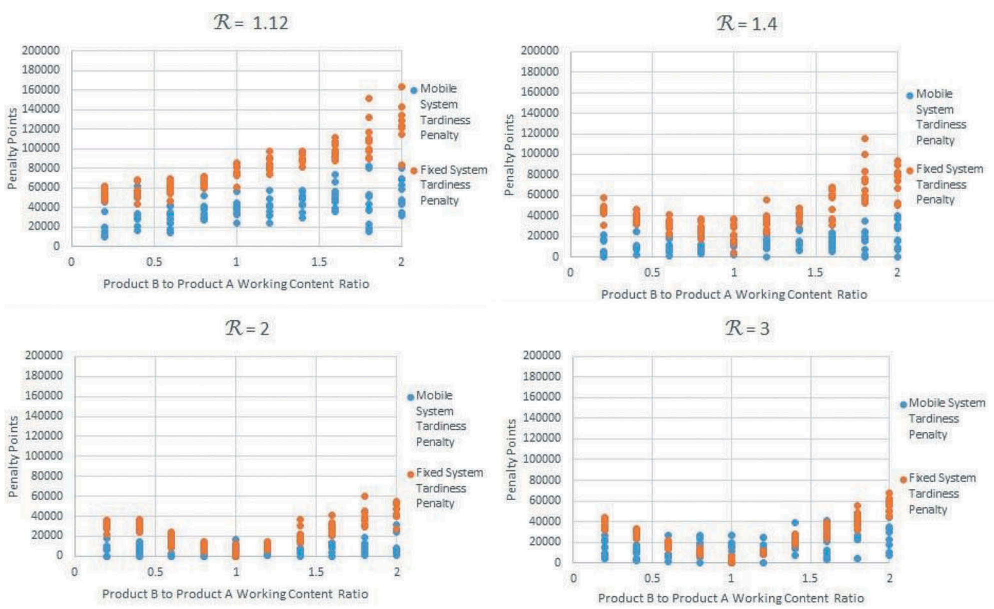

Figure 13. The results for the second experiment (2/2).

For the fixed system, the penalty points were mostly accumulated due to inherent physical limitations. This is because the fixed system was unable to change how much of its capacity it could allocate to any product. Consequently, it often became physically impossible to meet the set due times as shown in Figure 14. The figure is an illustration of how the mobile system can reallocate a freed resource to another job. In this case, *IF = 0* and product B's working content is 3 times greater than that of product A. The advantage of mobility enabled MM_1 to switch over to product B once it had completed product A and consequently finish it sooner. The dedicated system was unable to do so unless the crane system could supply it with the next product soon enough and would not be needed for some time. In addition to underutilisation, it missed the due time of product B and got penalised. The difference is further amplified by the fact that the dedicated system can only choose between two workstations, whereas the mobile system has the freedom to go to any of them.

The simulation results confirm that a dynamic system using mobile robots is naturally more flexible as it can freely choose which products it works on and in which sequence. The dedicated system is much more constrained to adapt to non-homogeneous production scenarios and adjust to bottlenecks. These results reflect challenges observed in comparable production systems in the aerospace industry.

The mobile system's ability to control work rates on selected products is vital when considering the dynamic nature of some markets for manufacturing goods. Fluctuations in schedules strongly affect the production management complexity and sometimes lead to unnecessary monetary losses in manufacturing plants with static shop floor layouts. Furthermore, there is no sign that the mentioned schedule disruptions will become less frequent at any point in the near future.

6. Conclusions

In this paper, a traditional, fixed automation system was compared to a mobile robot-based system in the context of large structure assembly. The comparison included scenarios of various product supply bottlenecks and product mixes for the two systems with equal manufacturing capacity. Several significant conclusions can be drawn from the work. Firstly, the freedom to distribute manufacturing resources depending on production requirements and imposed constraints (bottlenecks) is a great benefit of dynamic, mobile systems. The results show that it is much easier to maximise the utilisation of the manufacturing resources in

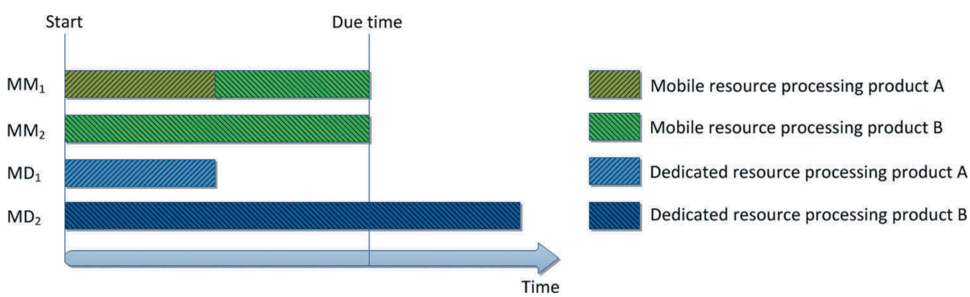

Figure 14. The difference in the ability to distribute manufacturing resources.

a dynamic system as it is less constrained. Hence, it enables manufacturers to either better fit the designed capacity of the manufacturing system to any bottleneck system or provide the freedom to reallocate a number of mobile robots to other tasks.

Considering that the mobile system, even with a simple control model, outperformed the fixed system in several of investigated scenarios (higher utilisation, higher control over product delivery times), it is evident that there is much more potential for such dynamic and adaptive shop floor layouts in the manufacturing industry. Clearly, more sophisticated decision-making models for the dynamic scheduling of mobile robots should lead to further benefits. Therefore, for the reasons mentioned under the related work and, further affirmed by conclusions of this paper, it is recognisable that there is great potential for dynamic shop floor layouts that consist of mobile robots.

Still, a number of challenges must be solved before mobile systems can be deployed on an industrial scale. Those challenges include the dynamics and decision-making models for mobile robots. In our further work, we propose different self-organisation models for mobile robots and compare them in order to be able to select the most suitable ones in a range of scenarios.

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