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Simulation of a generic flexible assembly system

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Abstract. During the early 1980s, the concept of a flexible assembly machine was first suggested by Hounsfield (1983). Following this, a variety of research projects have been conducted in an attempt to develop a flexible assembly system that is functional and economically viable. The most significant contribution has been made by the EURICA EU 321 – FAMOS – INFACT[1] project. However, despite the developments made during these projects, no industrial based system exists today. This paper presents a simulation model of a novel concept for a multi-station flexible automatic assembly machine, and examines the application of a rule based control strategy for the control of a materials handling system used in such a system.

1. Introduction

Before discussing flexible assembly it is important to understand the limitations of traditional dedicated assembly. Dedicated assembly is a mass production technology that was developed in the early 1900s by Henry Ford, to assemble a unique product in very large volumes, and this led to a very cost effective solution. Dedicated assembly automates the assembly task by breaking it down into simple operations that can be conducted by a series of workheads, the assembly being built up as it passes down the line. Parts are supplied in bulk, placed in individual parts feeders and presented to automatic workheads, which insert them into the part assembly at high speed. This form of assembly can achieve cycle times of as little as 1 second per assembly.

As dedicated assembly machines are only suitable for a single product, any significant product design change will result in considerable assembly machine redesign costs, and lengthy reconfiguration time. It is also clear that such equipment can only be justified for large production volumes, as the equipment cost is spread over the life of a single product. For this reason, the application of dedicated assembly has traditionally been restricted to high volume production. Furthermore, the world market is demanding greater product variety, consistent high quality, shorter lead times, competitively priced products and rapid new product introduction. In Scandinavian countries, these factors are now accompanied by increasing labour costs.

In the main, product assembly has remained a manual process, being subject to quality variations, fluctuations in productivity, fluctuations in labour rates and health and safety issues. In an attempt to reduce the cost of product assembly, many European companies have moved their assembly plants to lower cost regions. However, this is not always the ideal solution as it increases transportation costs, places a physical barrier between design and production and suffers from quality variations.

The introduction of semi-automatic assembly (see figure 1) has been one approach adopted by industry to counter the problems associated with manual assembly. Semi-automatic assembly automates critical parts of the assembly sequence, such as screwing or push-fit operations whilst an operator performs the part feeding and positioning tasks. This enables the manual assembly tasks that traditionally suffer from quality variations to be controlled using automation and the costly part feeding and manipulation tasks to be performed using low cost labour. However, semi-automatic assembly still requires a significant investment in dedicated tooling and remains subject to fluctuations in production rates, and fluctuations in labour rates.

The advantages of assembling in low cost regions can be eliminated if sufficient automation can be introduced into the assembly system (Fieldman *et al.* 1996), as the production system is no longer reliant on large numbers of people. The assembly plant can then be placed close to the customer market to reduce logistical costs.

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[1] http://www.3.eureka.be/home/

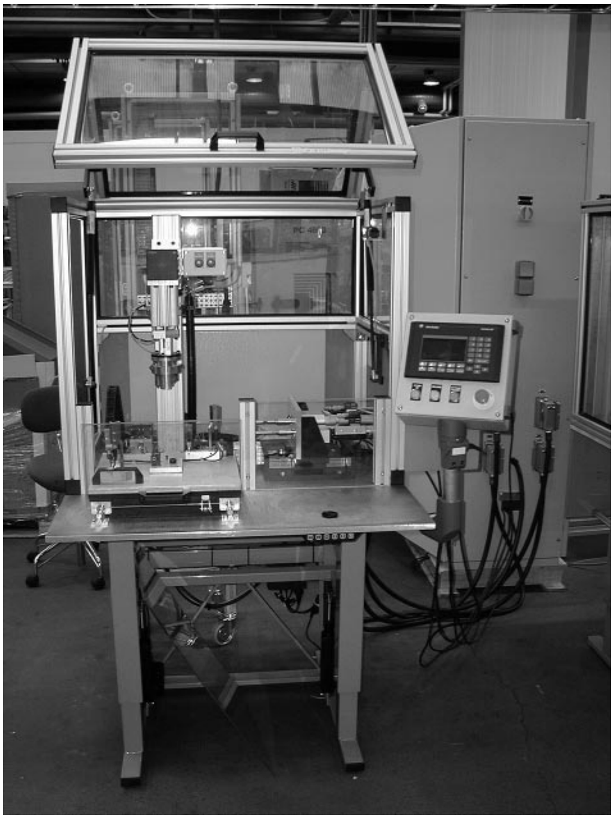

Figure 1. A semi-automatic assembly station.

The driving factor behind the design and development of flexible assembly systems is economics. As previously stated, it is not economically viable to build a dedicated assembly machine for small batch production quantities (30 000 to 500 000 units/year), as the piece part cost of assembly will be too high. The main goal, therefore, behind the development of a flexible assembly machine is the minimization of special purpose equipment, i.e. the equipment that can be amortized against the product. This will allow more than just one product type to be assembled on the machine and the machine cost to be spread over the production of more products.

Flexible assembly utilizes assembly robots and flexible part feeders in order to create a hybrid of manual, semi-automatic and dedicated assembly that is capable of small batch, large product variety production. The flexible assembly machine can be compared with a CNC machining station (see figure 2). Part programs, fixtures, tools and raw components are the system input, and finished products are the result.

There are three basic automatic flexible assembly system configurations, Single Station, Multiple Station and Automatic Flexible Assembly Line. Figure 3 shows a Single Station system, the assembly robot (manipulator) is located at the centre of the system and the parts feeders are located at the perimeter of the manipulator work zone. As a single manipulator performs all of the assembly tasks in series, the assembly time can become long if the assembly has many parts. If the number of parts in an assembly becomes too large, it may not be possible to fit them around the manipulator perimeter and a larger manipulator will have to overcome these problems, a Multiple Station layout can be used (see figure 4). The assembly operation is broken down into small groups of tasks performed at a number of assembly stations, the manipulator visits each of the assembly stations progressively. In order to make this possible, a fixture transfer system is required that increases the system cost. This approach enables

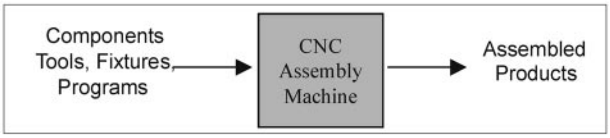

Figure 2. The CNC assembly machine.

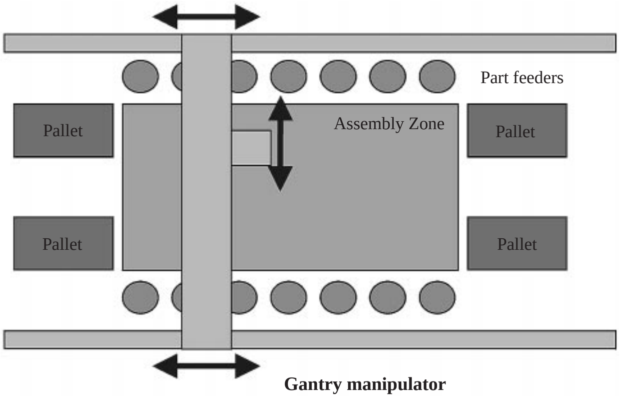

Figure 3. Schematic of single station automatic flexible assembly cell.

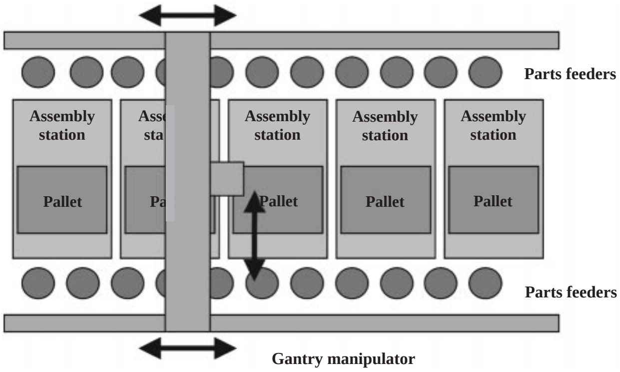

Figure 4. Schematic of multiple station flexible assembly system.

products with more components to be assembled with greater speed than a single station system.

To date the only commercially successful implementation of flexible assembly has been Flexible Line Assembly (see figure 5), where a number of manipulators are used to replace the dedicated workheads used in dedicated assembly lines, each manipulator performing a few assembly tasks at each assembly station positioned along an indexing transfer system. Such assembly systems are capable of high volume production of a single product having many variants, for example, the Sony Walkman or the assembly of video cameras (Whitney, 1999). The commercial success of these systems is due to the high production volumes of a single product, making the cost per unit of production economically acceptable.

The development of a generic flexible assembly system involves the design, selection and integration of a number of different mechanical systems in order to develop an assembly system that is capable of assembling a wide variety of products having an unknown specification. A specific system configuration is dependent on a variety of factors, such as product size, weight, component insertion direction, and manipulator geometry.

The concept of flexible assembly was first introduced by Hounsfield (1983). It was argued that such systems would be used to assemble the middle range of production volume between manual assembly and dedicated assembly (Lotter 1986). Twenty years later, no such systems exist as commercially available systems, and low volume assembly remains a manual or semi-automatic process, despite the rise in the cost of labour by 50%, a 70% reduction in the cost of robot technology and a significant improvement in the performance of robotic technology (Delgado 2001).

Edmondson and Redford (2001a) identified that the reason why flexible assembly was never implemented during the 1980s was because the cost of the technology was too high. Edmondson and Redford (2001a) also identified that, owing to the increase in labour costs and reduction in the cost of robots, flexible assembly can now offer significant savings over semi-automatic assembly and, in some cases, manual assembly for low and medium volume assembly.

Based on the above findings a novel concept (Patent Application No PA 2001 00045) for a multi-station flexible automatic assembly machine has been developed (Edmondson and Redford 2001b, c, d, e and f). An isometric view of the multi-station flexible automatic assembly station can be seen in figure 6.

This paper examines the application of a rule-based control strategy for the control of the materials handling system used in the multi-station flexible automatic assembly system.

2. Assembly workspace layout

Edmondson and Redford (2001c) identified that the most suitable layout for the various assembly cell elements is as shown in figure 7.

Two assembly fixtures are used in the assembly cell so that the manipulator can move directly to the second assembly fixture when all of the assembly tasks on the first assembly fixture have been completed, whilst the materials handling system removes and replaces the completed fixture of assemblies. This allows the first assembly fixture to be removed and replaced by the materials handling system without the need for the manipulator to stop working, hence maximizing the manipulator utilization. Furthermore, the time the manipulator spends performing gripper and tool changes is minimized by assembling in multiples of products on each fixture; in this way, the time taken to perform a gripper change is distributed

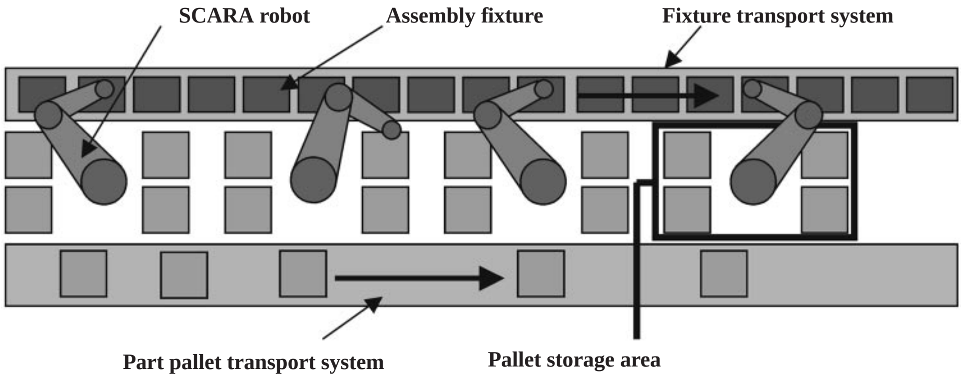

Figure 5. Schematic of flexible assembly line.

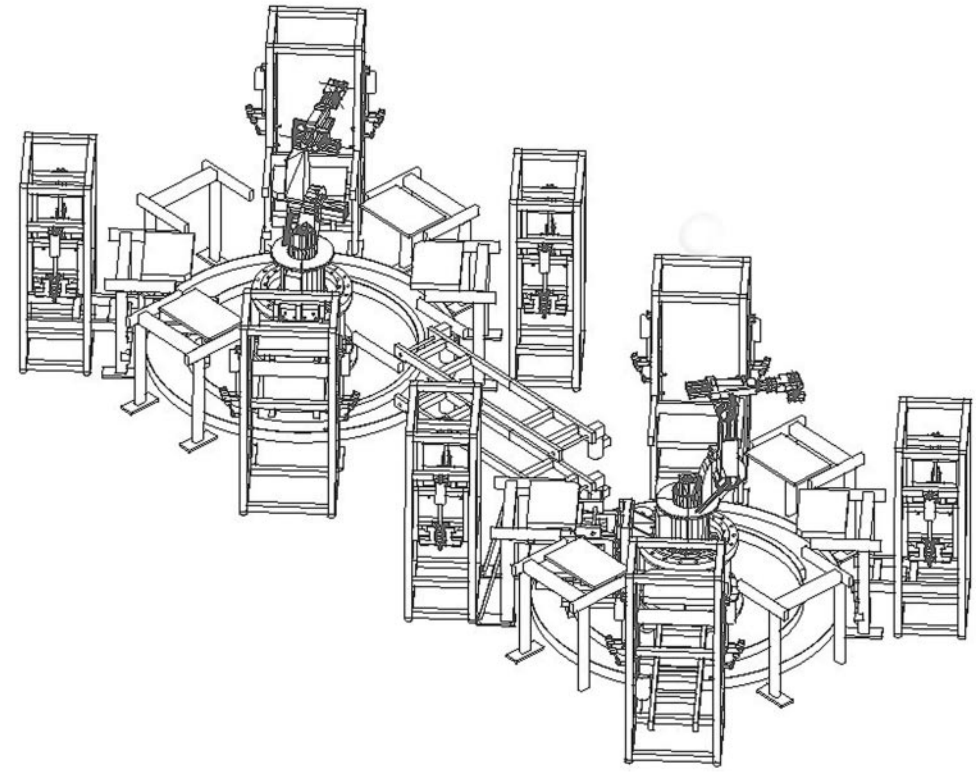

Figure 6. Isometric view of multi-station flexible automatic assembly system.

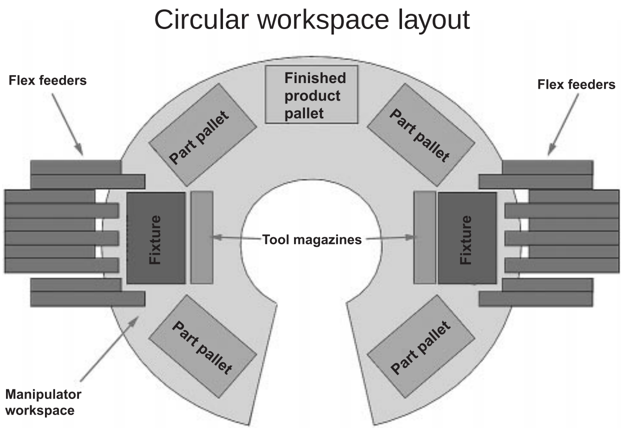

Figure 7. Assembly cell layout.

across a number of products as opposed to a single product, and the materials handling system is not required to replace an assembly fixture for each product assembled.

In order to achieve an appropriate production rate, a number of cells can be linked together to form an assembly line (see figure 8). Each assembly cell has a self-contained materials handling system, which interacts with the other assembly systems via a transfer mechanism. The result is that no increase in demand on the material handling system is experienced when a series of cells are linked together, and it is unlikely that the manipulators will have to wait for the handling system to supply parts.

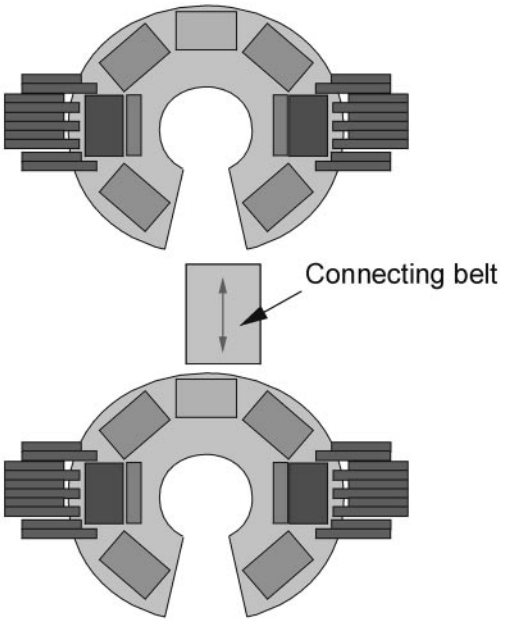

Figure 8. Flexible assembly cell line.

3. Materials handling system

The multi-station flexible automatic assembly machine can be considered as two basic mechanical systems which operate in parallel; the anthropomorphic manipulator, which performs the actual assembly task, and the materials handling equipment, which ensures that the manipulator is fed with the correct parts, fixtures and tools at the correct time and place, whilst performing other functions such as finished product removal from the assembly area.

Redford (1991) lists the total material handling requirements as follows:

The handling of pieceparts into the system. Pieceparts are categorized into two groups; those which can be handled using traditional small parts feeders, e.g. vibratory bowl feeders, and those which cannot be supplied using small parts feeders.

The handling of pallets, fixtures and tools. Apart from feeding pieceparts to the assembly system, the materials handling system will also be required to handle pallets of parts, assembly fixtures and the transfer of tools in and out of the assembly machine.

The removal of the completed product from the system. Finished assemblies need to be removed from the assembly fixture, and this function is performed by the manipulator picking the product from the fixture and transferring it to the material removal system. This can take the form of a simple output shoot that deposits the product into a bin of other finished products in a pseudo-random manner. However, in most cases, the product has to be handled by some other form of equipment, e.g. test, processing or packaging; hence, it would be logical to keep the product's position and orientation. This can be performed using some form of mechanical transfer device, which moves the product directly to the next process. Alternatively, if the proceeding process is not in close proximity to the assembly system or a storage buffer is required, the products can be placed in some form of packaging, e.g. palletized or magazined, so that the next process can automatically unload the packaging.

The accommodation of operations external to the assembly cell. Many electromechanical products require assembly tasks or processes that cannot be incorporated into the assembly machine due to economic, or technical reasons. If these products are to be assembled automatically, some form of transfer system needs to be incorporated to enable the transfer of partly finished assemblies to and from the external processes.

The transportation of partially finished products to and from rework. It is inevitable that faults will occur occasionally during the assembly operation. It is generally accepted that there are three basic corrective actions that can be performed.

(1) Stop the equipment and wait for manual assistance.
(2) Attempt automatic recovery.
(3) Remove the partially completed product from the system, carry out reparation work offline and return the reworked product to the system for completion.

The first two activities, being in-cell activities, place no demand on the materials handling system, while the third solution would require the application of the materials handling system.

Redford (1991) also suggested that the materials handling function should be performed using two systems; flexible small parts feeders for pieceparts (Edmondson and Redford 2001f) and a pallet system for all other handling operations due to the commonality and frequency of material handling motions into and out of the assembly system.

To meet these requirements it was identified (Edmondson and Redford 2001d) that the materials handling system must be capable of removing and replacing one pallet at a time without moving any other pallets or fixtures. For example, when a pallet is empty it must be replaced without interrupting activities being conducted on other pallets. It was found that this function could be achieved using a cylindrical manipulator mounted beneath the anthropomorphic manipulator, see figure 9.

Parts supplied to the system on pallets are fed from pallet magazines located around the circumference of the articulated robot's workspace. Pallets are removed from the base of the pallet stack and fed to the cylindrical robot, which places them in the required pallet location. A buffer belt can be added to the pallet magazine, which automatically reloads the magazine enabling longer periods of unmanned production. Empty pallets are fed to empty pallet magazines located around the assembly cell or at the middle belt joining the two robot cells. The same system can also be used to store and automatically change the assembly fixtures.

4. Strategy for operating the materials handling system

Based on the development of a flexible assembly machine using two gantry manipulators to perform assembly tasks, and a single pallet shuttle running under the length of the gantry manipulator's work-

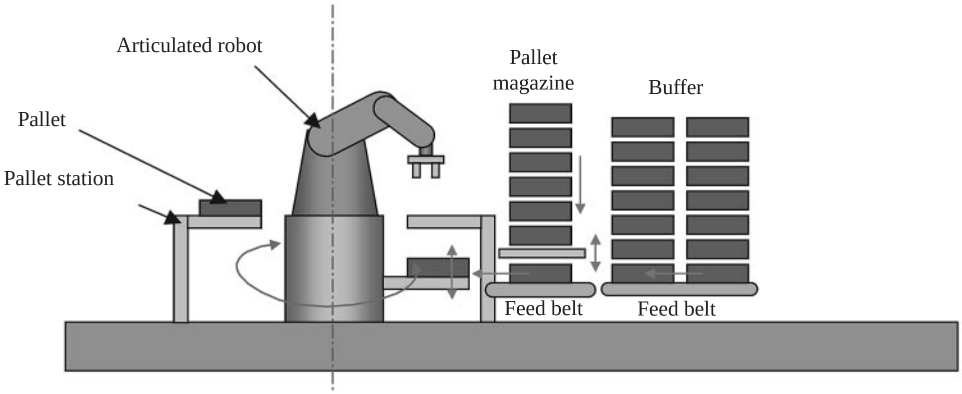

Figure 9. Cross-section of pallet handling system (EU PA 2001 00045).

space, Redford and Dailami (1998) proposed that the pallet shuttle could be controlled using a scheduling method that would schedule the materials handling tasks so that they would occur during non-productive periods of the assembly manipulator's work cycle, for instance during tool and gripper changes. It was assumed that the pallet shuttle would run out of capacity and be unable to meet the material handling requirements of the two manipulators. Hence, it was suggested that the control logic of the pallet shuttle should be reprogrammed for each new product the machine was to assemble, based on the output of the scheduling exercise, in an attempt to optimize the pallet shuttle's utilization.

The multi-station flexible automatic assembly system proposed by Edmondson and Redford (2001d) proposes the use of a single pallet shuttle for each assembly manipulator in the assembly system, as opposed to a single pallet shuttle for all manipulators in the system, as a means of avoiding the lack of materials handling capacity. This paper examines the possibility of controlling the pallet shuttle using a set of standard rules for all products. The rules determining the reaction of the pallet shuttle are in response to signals generated during the assembly process, i.e. the material handling system does not have a fixed operating cycle but performs tasks based on the requirements of the assembly process. The rules were developed iteratively during the construction of the simulation model, and are listed as follows in order of priority.

(1) *Empty the middle belt.* When a fixture is placed at the end of the middle belt it should be removed as soon as the cylindrical robot is free.
(2) *Remove and replace the finished parts pallet.* If finished products are placed on a pallet, the pallet should be removed and replaced as soon as possible when it is full.

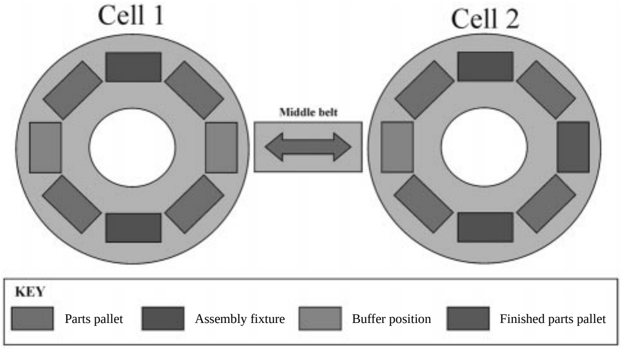

Figure 10. Schematic of pallet positions (EU PA 2001 00045).

(3) *Remove completed fixtures.* When fixtures have completed the assembly cycle move them to the next cell.
(4) *Replace empty pallets.*

5. Materials handling system performance

In order to measure the material handling systems performance, the following variables were tested.

(1) *Time to effect a pallet or fixture move.* The speed at which the pallet shuttle and middle belt function has a direct impact on the point at which the pallet system runs out of capacity. The maximum speed at which the pallets and fixtures can be moved is dependent on the stability of the parts in the pallets during transportation, which is dependent on many variables such as pallet and fixture design, pallet, part and fixture weight and the acceleration and deceleration forces the pallets and fixtures are subjected to. For system stability it is important to operate well below the maximum pallet and fixture velocities.

(2) *The configuration of the middle belt.* The middle belt is used to remove empty pallets, transfer fixtures of semi-finished assemblies and return empty fixtures to cell 1 from cell 2. Hence, the middle belt will need to be able to transfer pallets and fixtures in two directions, serve both assembly cells, and have an ejection mechanism for empty parts pallets. It is therefore anticipated that the middle belt will be a bottleneck; hence, it may be necessary to add an extra middle belt to increase the capacity of the system.

(3) *Distribution of the assembly task across the two cells.* The assembly task is divided across the two assembly cells. However, it is not always possible to divide the assembly task equally across both cells, resulting in one of the cells acting as a bottleneck—how this effects the rest of the system is unknown.

(4) *Assembly cycle time.* The shorter the assembly cycle time the greater the frequency of the pallet shuttle to transfer the assembly fixture. It is therefore important to identify the shortest cycle time that can be accommodated before the material handling system runs out of capacity.

(5) *Number of parts on pallets.* Reducing the number of parts on pallets will increase the demand on the materials handling system, as the pallets will require replacing more frequently. Hence, identifying the number of parts per pallet and the assembly cycle time at which the pallet system begins to lose capacity is important.

(6) *Number of fixtures.* The number of fixtures in the system needs to be determined. If there are insufficient fixtures available for the manipulators, the manipulators will be unable to assemble products and capacity will be lost. However, as there is limited buffer space the machine, if there are too many fixtures in the system it will begin to block up and eventually a dead lock will occur, resulting in the system losing capacity.

(7) *Number of products on fixtures.* As with the number of parts on pallets, the number of parts on a fixture will affect the demand on the materials handling system. Therefore, identifying the ratio of the number of parts on a fixture to the cycle time at which the pallet system begins to lose capacity is important.

6. Simulation model

The simulation model was created using Automod 3D simulation software. A 3D simulation package was chosen because it allows the motions of the materials handling system to be animated in detail, making the validation and experimentation process simpler to perform. The 3D graphics were also very useful when presenting the system concept to others. The benefits of 3D simulation packages and some of the CAD modelling techniques are discussed further by Ranky (1986).

The level of graphical detail included in the model was limited to a schematic representation (see figure 11). Small part feeders have not been included in the model as the focus of the simulation exercise was to study the materials handling system in detail and only to simulate the activity of the assembly manipulator in limited detail. For this reason, the assembly process at each fixture position was modelled as the total cycle time for assembling all parts and products on each fixture plus tool and gripper change times. The effect of using small parts feeders can be modelled by changing the number of parts fed by pallet, and hence the demand on the materials handling system.

The models variables (assembly cycle time, number of parts on fixtures, number of fixtures, number of parts on fixtures and the materials handling systems performance) were initialised from an external text file (see Appendix A).

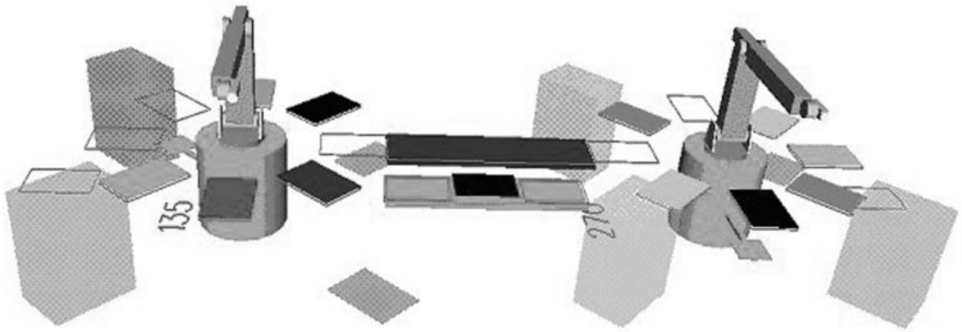

Figure 11. Simulation model of flexible assembly system.

6.1. *Model validation*

The validation of the model was conducted using a Grundfos OEM Hydroblock product (see figure 12). The parts that were fed on pallets and their location in the machine (see figure 13) is listed in table 1.

The materials handling system task times were estimated based on pallet and fixture velocities in traditional pallet handling systems (see Appendix A).

The model was validated by comparing its output over a ten-hour period with the expected output, and by observing the model's compliance with the scheduling rules. The simulation input data that were used are as follows.

- Five products on each assembly fixture.
- Cycle time in cell 1=250 seconds per fixture.
- Cycle time in cell 2=240 seconds per fixture.
- Parts on pallet 1 cell 1=15 units.
- Parts on pallet 2 cell 1=25 units.
- Parts on pallet 1 cell 2=25 units.
- Parts on finished product pallet=20 units.
- Single transfer belt between assembly cells.

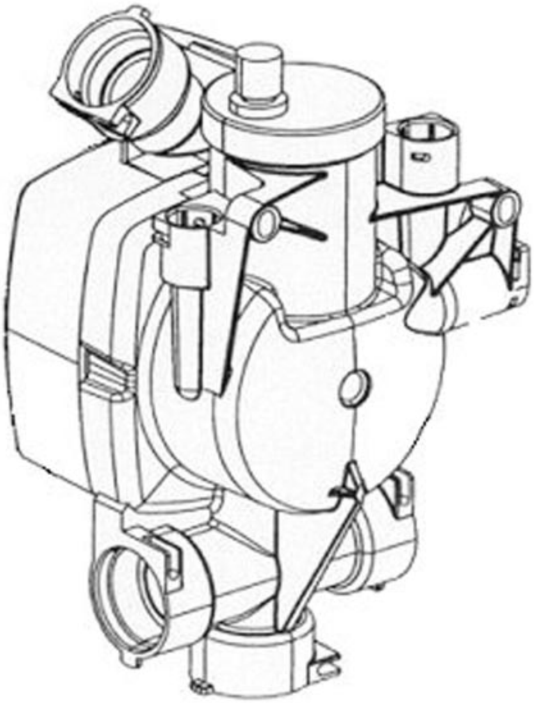

Figure 12. Grundfos OEM Hydroblock.

6.1.1. *Expected output.* Cell 1: 3600 seconds per hour/(250 seconds + 3 seconds)=14.22 fixtures

The additional 3 seconds is the time taken at the end of each assembly cycle for the assembly manipulator to rotate from one assembly fixture to another. Hence: 14.22 fixtures × 5 items per fixture=71.15 units per hour

Cell 2: 3600 seconds per hour/(240 seconds + 3 seconds)=14.81 per fixtures. Hence: 14.81 fixtures × 3 items per fixture=74.05 units per hour

As the output of the system is based on the slowest cycle time the expected production rate of the assembly system is 71.15 units per hour.

6.1.2. *Estimated number of fixtures required:* The number of fixtures that are required to ensure there are sufficient fixtures available for the manipulator can be calculated using the flow time of one fixture (Lenz, 1988). The flow time of one fixture is the time it takes for a fixture to circulate through the assembly system i.e. the total of both assembly cycle times plus the fixture transport times. This can be estimated as shown in table 2.

Hence, in 1 hour a fixture can rotate through the system:

3600 seconds/560.8 seconds=6.41 times.

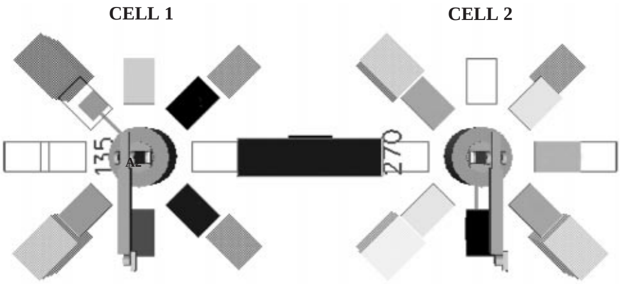

Figure 13. Pallet locations.

Table 1. Pallet locations and specifications.

Component	Assembly task	Pallet	Pallet positions	Parts per pallets
Hydroblock base	1	Cell 1 pallet 1	Cell 1 position: A1	5
Top chamber	1	Cell 1 pallet 2	Cell 1 position: A2	5
Pump motor	2	Cell 2 pallet 1	Cell 2 position: B1	5
Finished product	2	B-out	Cell 2 Position: B-out	5

Table 2. Estimation of fixture flow time.

Activity	Cycle time (seconds)
Cycle time in cell 1	250
Cycle time in cell 2	240
Estimation of time taken to move a fixture from an assembly station in cell 1 to an assembly station in cell 2 and back again:	
Move 360 degrees to assembly station	7.2
Move pallet shuttle from upper to lower level	2.2
Collect fixture	1.2
Move pallet shuttle from upper to lower level	2.2
Rotate 90 degrees	1.8
Move pallet shuttle from upper to lower level	2.2
Deliver fixture to middle belt	1.8
Middle belt transportation time	7
Collect pallet	1.8
Move pallet shuttle from upper to lower level	2.2
Rotate 90 degrees	1.8
Move from lower to upper level	2.2
Deliver pallet	1.8
Total:	35.4
The procedure is repeated when returning the pallet, hence, multiply by 2:	**70.8**
Estimated flow time:	**560.8**

If 14.22 fixtures are required per hour by a single assembly manipulator, the number of fixtures that are required to flow around the assembly system is:

14.22 fixtures/6.41=2.21 fixtures ≈ 3 fixtures.

The flow time is only an estimate because the materials handling system performs other activities, such as replacing empty pallets or removing pallets of finished products, these activities can delay the pallet transfer operation, resulting in a longer flow time than predicted. However, the initial estimate is sufficient to identify the approximate number of fixtures required by the system for the first simulation run.

6.2. *Validation results*

The following results were obtained from the simulation model from a 10-hour simulation run.

Output statistics

Number of items produced in cell 1	708 units
Number of items produced in cell 2	702 units
Flow time per fixture 6	52.45 seconds

Resource statistics

Pallet shuttle 1	33.6%
Pallet shuttle 2	31.4%
Manipulator 1	100%
Manipulator 2	94.8%
Transfer belt	59.6%

From the above it can be seen that the model predicts that the assembly system will be operating at 100% efficiency, i.e. Manipulator 1 never has to wait on the materials handling system. The 5.2% loss in efficiency at Robot 2 is because the assembly cycle time in cell 2 is shorter than in cell 1 hence, Robot 2 spends 5.2% of the time waiting for assemblies from Robot 1. Based on this and the agreement of the model's behaviour with the scheduling rules, it was concluded that the model is an accurate representation of the assembly system.

However, the estimated flow time of 560 seconds is incorrect as the materials handling cycle is 92 seconds too short and should be 162.8 seconds; hence, the estimation of the number of fixtures that are required needs to be checked. Inserting the actual flow time into the previous calculations gives the following:

In 1 hour, a fixture can rotate through the system:

3600 seconds/652.45 seconds=5.52 times.

If 14.22 fixtures are required per hour by a single assembly manipulator, the number of fixtures that are required to flow around the assembly system is:

14.22 fixtures /5.52 =2.58 fixtures ≈ 3 fixtures.

This is obvious because if the system required more fixtures it would not be able to operate with 100% efficiency. Note, the model contains no random elements; hence, when performing tests, simulation runs are not required to build up a statistical average.

7. Simulation model results

In order to identify whether one or two connecting belts should be used between the two assembly cells, the capacity of each solution was identified. The point at which each system begins to lose capacity was identified by gradually reducing the assembly cycle time in both cells, and the output of each system was recorded (see figure 14).

From figure 14, it can be seen that only a slight improvement in system performance is obtained for shorter assembly times when using the double belt system. The explanation for this can be seen when examining the utilization of the connecting belts for each system (see figure 15). Figure 15 shows that the connecting belt in the single belt system approaches a utilisation of 90% and becomes a 'bottleneck' when operating with cycle times of

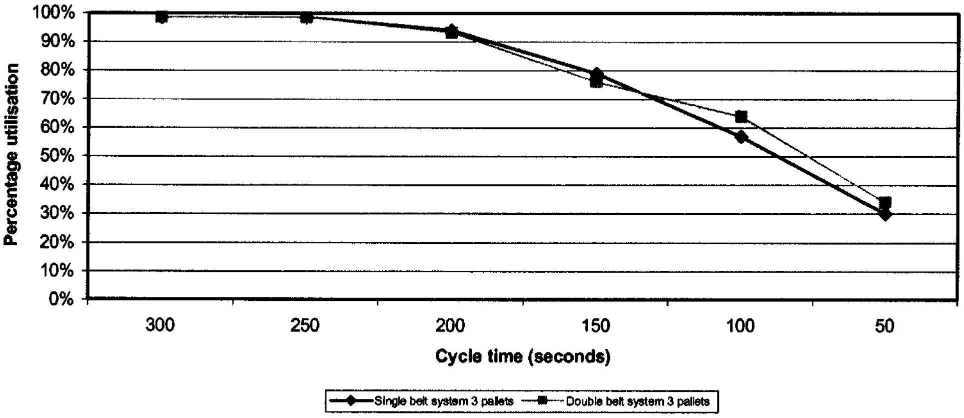

Figure 14. Comparison of double and single belt systems.

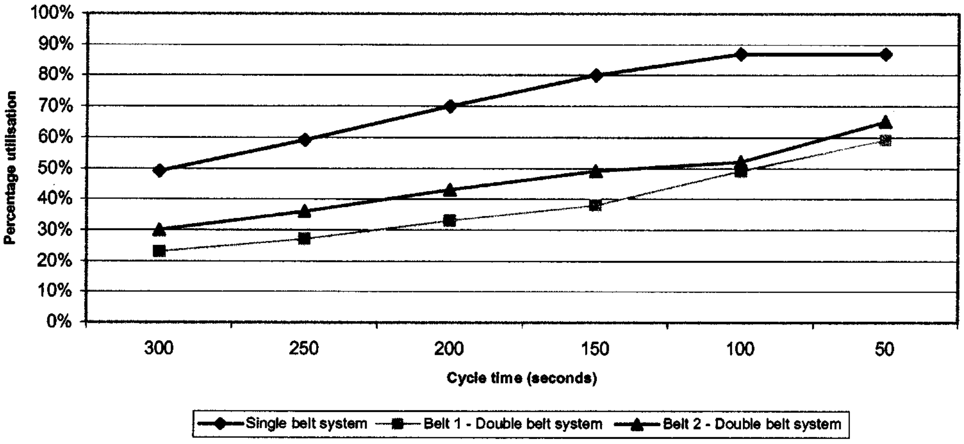

Figure 15. Utilization of connecting belts.

50 seconds or below. The connecting belts in the double belt system reach a utilization of 65%, which explains the increase in performance.

Figure 16 shows the utilization of all the materials handling system elements in the double belt system. It can be seen that, although the utilization of the second pallet shuttle is over 76% when operating with a cycle time of 50%, the materials handling system has spare capacity. Therefore, the low system efficiency must be attributed to a shortage of fixtures in the system when the cycle time is less than 250 seconds (see figure 13).

To check this, the estimated number of fixtures can be calculated when operating with a 50 second cycle time in both cells.

7.1. *Expected output*

Cell 1: 3600 seconds per hour/(50 seconds + 3 seconds)=67.92 fixtures.

The additional 3 seconds is the time taken at the end of each assembly cycle for the assembly manipulator to rotate from one assembly fixture to another.

Hence: 67.92 fixtures × 5 items per fixture=339.6 units per hour.

Cell 2: 3600 seconds per hour/(50 seconds + 3 seconds)=67.92 fixtures.

Hence: 67.92 fixtures × 5 items per fixture=339.6 units per hour.

In 1 hour, a fixture can rotate through the system: 3600 seconds/(50+3+50+3+162.8) seconds=13.39 times.

If 67.92 fixtures are required per hour by a single assembly manipulator the number of fixtures that are required to flow around the assembly system is:

67.92 fixtures /13.39 =5.07 fixtures ≈5 fixtures.

Based on this, the number of fixtures in the system was increased to five and the model was run over a 10-hour

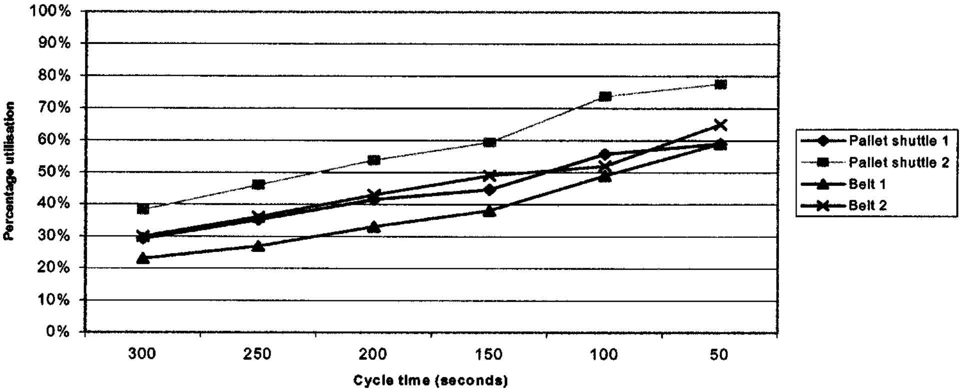

Figure 16. Utilization of materials handling system.

period. Increasing the number of fixtures in the system made no difference to the system's overall efficiency, which remained at 34%. The statistics of the system elements gained during the simulation run are as follows.

7.2. *Output statistics*

Number of items produced in cell 1	1179 units
Number of items produced in cell 2	1166 units
Flow time per fixture	648.81 seconds

7.3. *Resource statistics*

Pallet shuttle 1	82.9%
Pallet shuttle 2	78.0%
Manipulator 1	75.6%
Manipulator 2	34.4%
Connecting belt 1	64.7%
Connecting belt 2	61.8%

On examination of the utilization of the material handling system elements, it can be seen that the utilization of pallet shuttle 1 has increased by 24% due to the extra handling involved with the additional fixture. Based on the above, it can be concluded that no improvement in overall system efficiency was experienced because the system became blocked and the pallet shuttles became overloaded moving fixtures around the system, as there is a limited quantity of buffer space in the system. This conclusion can be validated by observing the system's performance when operating with four fixtures (see figure 17). When operating with four fixtures, the system has more fixture capacity than the three-fixture system and does not become blocked; hence, there is a slight improvement in the overall system efficiency.

7.4. *Adjusting the sequence of pallet and fixture changes*

Figure 18 shows the periods of activity for pallet shuttle 1, which clearly indicate that the pallet shuttle's activity comes in pulses. This means that the pallet shuttle does not have to reach 100% utilization before it becomes a bottleneck because, if the assembly cycle time is short enough, and the number of pallets that need changing at the end of an assembly cycle is large enough, then the pallet shuttle will not be able to remove and replace the pallets and fixture before the manipulator is ready to start the next assembly cycle. However, the pallet shuttle can stand idle between the pulses of demand. A method of overcoming this is to ensure that each task is not required at the same time; hence, reducing the number of tasks that need performing during each pulse of activity. For example, the replacement of parts pallets and fixture pallets could be performed at different times.

The number of parts on each of the parts pallets during the tests was equal (20 parts), this meant that both parts pallets required replacing for every fourth assembly pallet produced (a fixture having place for five assemblies); the finished assembly pallet only having capacity for 10 products had to be changed every second assembly fixture that was completed. Therefore, every fourth assembly pallet changed required both parts pallets and the finished parts pallet to be changed—in total, four pallets had to be changed in 53 seconds. As it takes approximately 181 seconds to replace four pallets, it is not surprising that the system loses capacity. The effect of changing the ratio of the number of parts on each of the parts pallets to 15 on

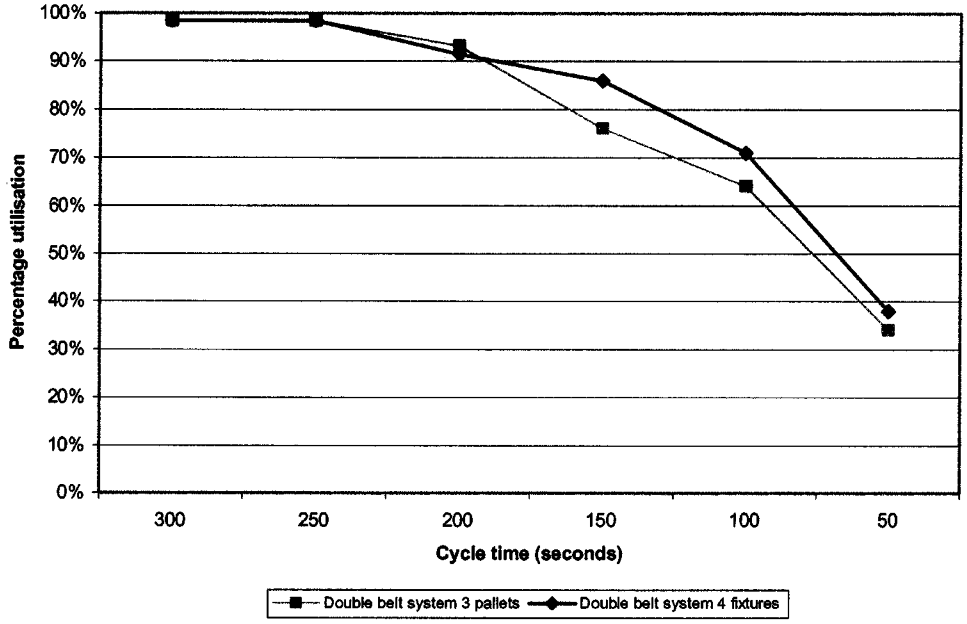

Figure 17. Comparison of three and four fixture systems.

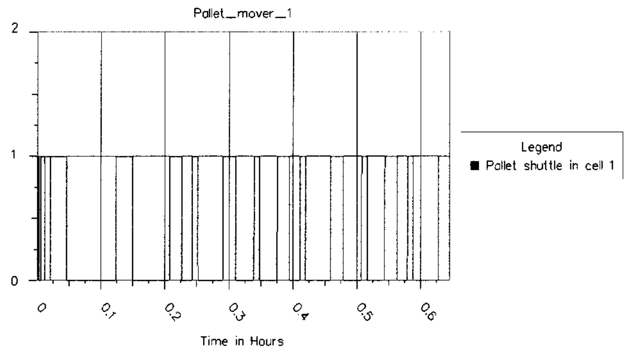

Figure 18. Pallet shuttle activity.

pallet 1 and 20 on pallet 2, so that both parts pallets are not always changed at the same time can be seen in figure 19.

It can be seen in figure 19 that sequencing the pallet changes does not increase the efficiency of the system when the fixtures have short cycle times, but it does move the point where performance begins to drop below 90% to the right of the graph.

Figure 20 shows the utilization of the material handling system elements for the sequenced pallet set-up.

From figure 20, it can be seen that the materials handling systems utilization increases as the cycle time reduces. It can also be seen that the second pallet shuttle has a higher utilization than the first, this is partly due to the extra pallet handling task it performs each time a finished product pallet is removed. Increasing the number of parts that can be carried on a finished product pallet, or replacing the pallet with an output belt reduces the demand on the second shuttle (see figure 21).

From figure 21, it can be seen that there is a slight reduction in the utilization, but not as much as expected. It is also clear from figure 21 that increasing the number of parts on the finished product pallet causes the utilization of the first part mover to increase by 12%. The reason for this is that the increase in the availability of pallet shuttle 2 (the bottleneck of the system) has resulted in an increase in the number of fixtures that can be fed to the assembly manipulator in cell 2, hence an increase in the number of fixtures returned to cell 1, which results in an increase of the overall system capacity. The increase in the materials handling system performance can also be seen by observing the flow time for a fixture, which drops from 412 to 330 seconds.

7.5. *Adjusting the number of parts on pallets*

When the materials handling system is operating with cycle times that are shorter than the time taken to replace the required parts pallets and fixtures at the end of each assembly cycle, it is possible to improve the system's performance by increasing the number of parts on the parts pallets so that the pallets do not have to be replaced as frequently (see figure 22).

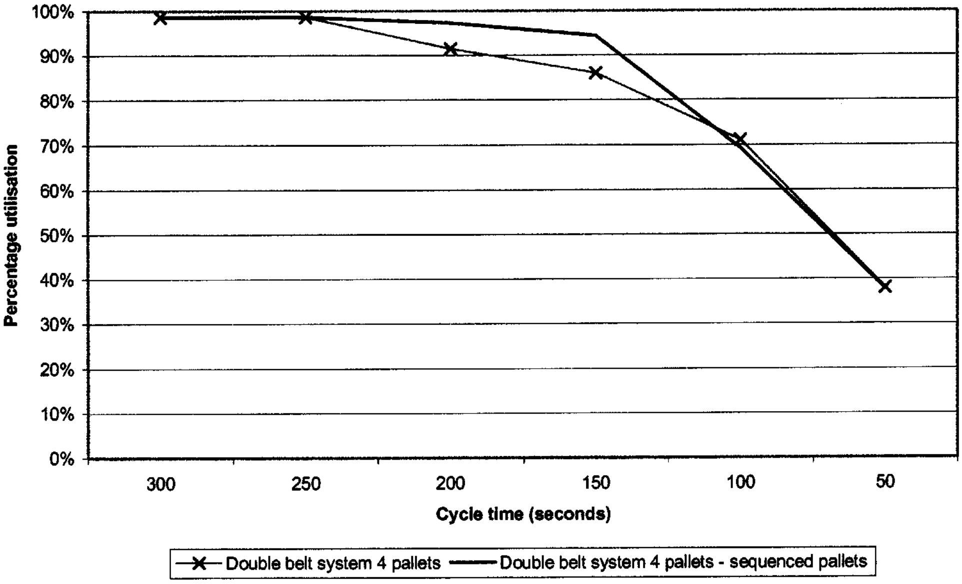

Figure 19. The effect of sequencing the parts pallet changes.

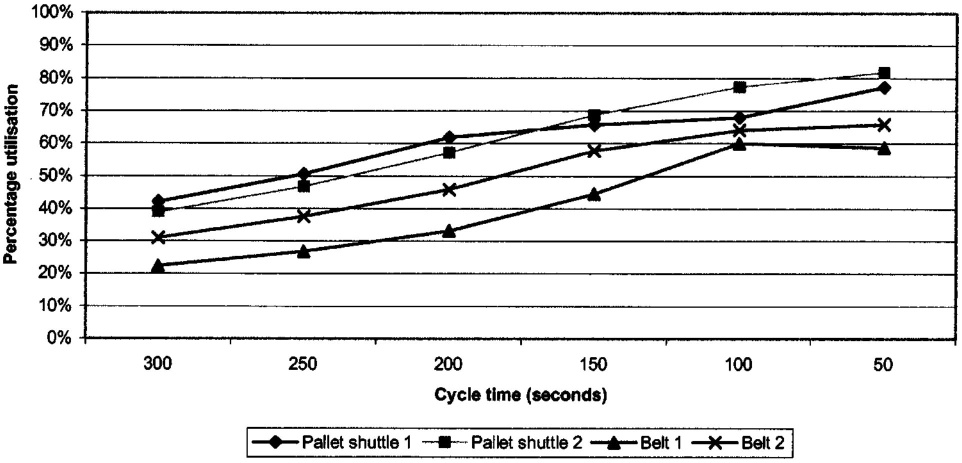

Figure 20. Utilization of materials handling system.

It should be noted that it is not always possible to increase the number of parts carried on a pallet as this is normally restricted by physical constraints. Therefore, the aim should be to fit as many parts onto a parts pallet as possible.

7.6. *Minimum assembly cycle time*

The minimum cycle time per fixture for different quantities of parts per parts pallet is shown in figure 23.

Using figure 23, it is possible to establish basic targets for assembly fixture cycle times and the number of parts that need to be on the parts pallets in order for the system to operate efficiently. For example, if the system operates with 25 parts per parts pallet, 5 parts per fixture and 25 assemblies per finished product pallet, the minimum assembly cycle time that the system can cope with before efficiency falls below 90% is 184 seconds. The Grundfos OEM product had an assembly time of 50 seconds per product, which would produce an efficiency of 43%. However, as multiples of products are assembled on each assembly fixture in order to reduce the time wasted performing gripper and tool changes, more realistic fixture assembly times are achieved. For example, the Grundfos OEM product is

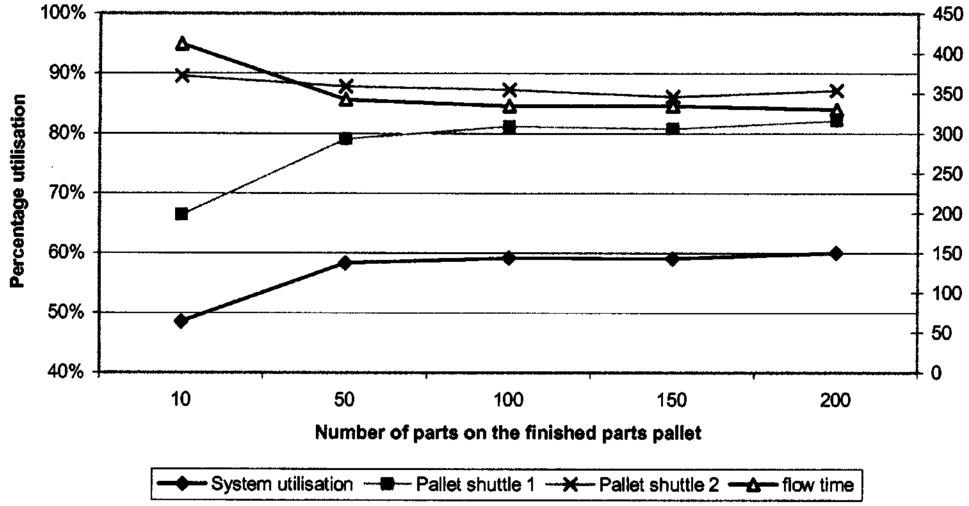

Figure 21. The effect of the finished parts pallet.

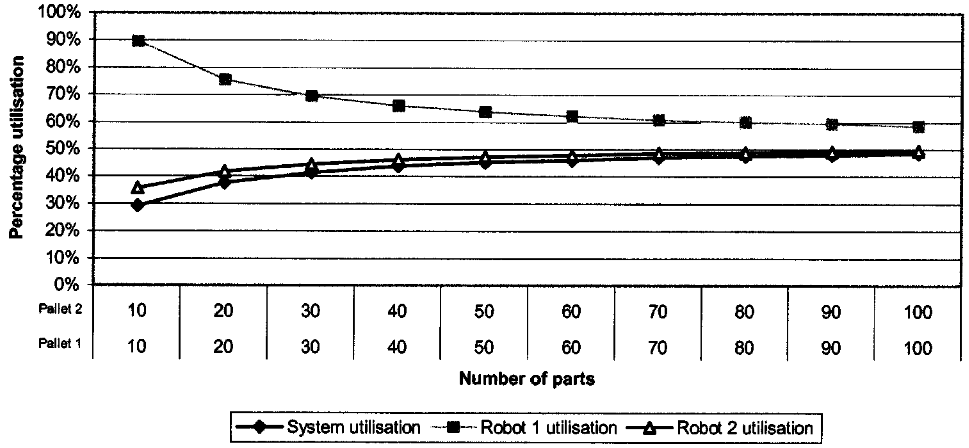

Figure 22. The effect of increasing the number of parts per parts pallet.

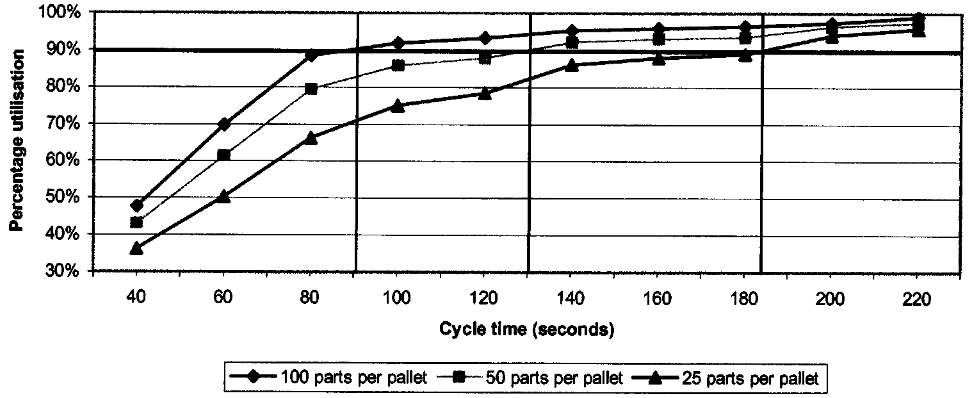

Figure 23. Optimal cycle time.

assembled in multiples of five producing a fixture assembly time of 250 seconds, which gives an efficiency of over 95%.

7.7. *Distribution of the assembly task across the two cells*

The effect of having different cycle time ratios for each assembly cell is shown in figure 24. It can be seen that the system has the greatest output when the cycle time is equally distributed across the two cells, this indicates that the system is balanced, and that both assembly cells have the same overall capacity.

8. Conclusions

(1) A materials handling system based on a cylindrical manipulator is appropriate for flexible assembly cells.
(2) The use of a cylindrical manipulator for materials handling enables pallet transportation in parallel to the assembly manipulator movements, resulting in a very efficient materials transfer system.
(3) It is possible to control the materials handling system using four standard rules.
(4) For cycle times greater than 250 seconds, three assembly fixtures can be used; cycle times below 250 seconds require four assembly fixtures.
(5) To maximize the efficiency of the materials handling system the following guidelines should be followed.

    (a) Maximize the number of assemblies per fixture.
    (b) Maximize the number of parts on part pallets.
    (c) Maximize the number of products on finished parts pallets.
    (d) Ensure that the number of parts on each pallet type is different by a factor of the number of assemblies on the assembly fixture.
    (e) Balance the total product assembly cycle time equally across both cells

9. Further work

Based on the successful outcome of the simulation tests, a prototype assembly machine will be constructed. The prototype machine will be used to analyse the assembly process, test the materials handling systems stability and run product assembly production trials.

Acknowledgements

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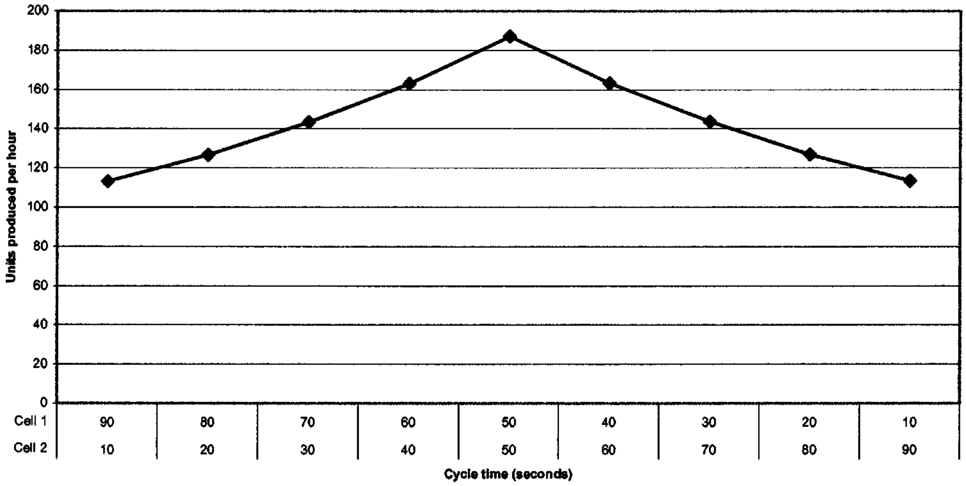

Figure 24. The effect of different cycle time ratios.

Appendix A: external text file

2	Number of connecting belts in the system
5	Number of fixtures in the system
50	Overall cycle time in seconds per fixture in cell 1
50	Overall cycle time in seconds per fixture in cell 2 including placing finished items on transport pallet
5	Items on a fixture in cell 1
5	Items on a fixture in cell 2
20	Items on pallet 1 in cell 1
20	Items on pallet 2 in cell 1
20	Items on pallet 1 in cell 2
20	Items on pallet 2 in cell 2
10	Finished items on pallet 3 in cell 2 – has to same number or a multiple of number on fixture 2
9	Time in seconds for transferring a pallet from a magazine or a fixture from a buffer onto mover
2.2	Time in seconds for moving from lower to upper level
1.2	Time in seconds for moving a pallet or fixture horizontal to/from correct position
1.2	Time in seconds for picking up a pallet or fixture from the working position
2.2	Time in seconds for moving from upper to lower level
1.0	Time in seconds for carefully placing a pallet or fixture onto the working position
3.0	Time in seconds for +/−180 degree rotation of robot
0.9	Time in seconds for +/−45 degree rotation of cylindrical robot
1.8	Time in seconds for +/−90 degree rotation of the cylindrical robot
2.7	Time in seconds for +/−135 degree rotation of the cylindrical robot
3.6	Time in seconds for +/−180 degree rotation of the cylindrical robot
4.5	Time in seconds for +/−225 degree rotation of the cylindrical robot
5.4	Time in seconds for +/−270 degree rotation of the cylindrical robot
6.3	Time in seconds for +/−315 degree rotation of the cylindrical robot
7.2	Time in seconds for +/−360 degree rotation of the cylindrical robot
7.0	Time in seconds for conveying a full fixture on the connecting belt
7.0	Time in seconds for conveying an empty fixture or pallet on the connecting belt

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