THE DESIGN AND DEVELOPMENT OF A RECONFIGURABLE MANUFACTURING SYSTEM

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ABSTRACT

As a result of increasing global industrial competition, it has become essential for world economies to implement an effective industrial strategy that reliably and quickly addresses sudden changes in product design. An emerging strategy that might enable industries to cope with rapidly changing product specifications is based on reconfiguring the manufacturing systems. In this paper, the authors present the development of a manufacturing system that will be easily reconfigurable. The developed manufacturing system exhibits the ability and potential for a rapid alteration of manufacturing capacity and the fast integration of new products into the existing manufacturing system.

OPSOMMING

As gevolg van toenemende wêreldwye industriële mededinging het dit noodsaaklik geword vir wêreld-ekonomieë om 'n effektiewe industriële strategie te implementeer om betroubaar en vinnig skielike veranderinge in produkontwerp te hanteer. 'n Nuwe strategie, wat nywerhede moontlik in staat kan stel om vinnig veranderende produkspesifikasies te hanteer, is gebaseer op herkonfigurasie van vervaardigingstelsels. In hierdie artikel word die ontwikkeling van 'n vervaardigingstelsel wat maklik her-konfigureerbaar is, bekend gestel. Die ontwikkelde vervaardigingstelsel toon die vermoë en potensiaal vir vinnige verandering van die vervaardigingskapasiteit en die vinnige integrasie van nuwe produkte in 'n bestaande produksiestelsel.

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1. INTRODUCTION

Manufacturing is the application of physical and chemical processes to alter the geometry, properties, and appearance of a given starting material (raw or semi-finished) to make parts or products. It is usually carried out in a sequence of operations, each bringing the material closer to the final stage. The arrangement of facilities to form this sequence of operations is referred to as a manufacturing system. Alternatively, a manufacturing system can be defined as the arrangement and operations of various manufacturing elements - such as machines, tools, material, people, and information - to produce a value-added physical, informational, or service product whose success and cost are characterised by the measurable parameters of the system design [1, 2]. These elements of a manufacturing system should be arranged in a co-ordinated fashion that enables the smooth functioning of the whole system, in order to make the organisation's goals and objectives achievable. This need is addressed in the process of designing the manufacturing system.

A reconfigurable system is one whose subsystems and/or subsystem configurations can be changed or modified after fabrication to serve a certain purpose better [3]. Koren et al. [4] define a reconfigurable manufacturing system as a manufacturing system designed from the outset for rapid change in structure, as well as hardware and software components, in order to adjust production capacity and functionality quickly, in response to sudden changes in market or regulatory requirements.

Since the Industrial Revolution, the dedicated manufacturing system (DMS) has been favoured for mass production, and most factories around the world make use of it. Mass production results in a low product unit price. Owing to the nature of the traditional dedicated manufacturing system, any slight change in product design may make further production of the new product on the line difficult, if not impossible. The reason is that DMS, by design, is made rigid to enhance mass production for profitable and cost-effective purposes. But this type of manufacturing system can only be effective in a stable market. Today's market is highly competitive, dynamic, and customer-driven - a market scenario characterised by increased customer demand for a wider variety of products in unpredictable quantities [5]. A flexible manufacturing system (FMS) is the alternative that readily comes to mind, owing to the shortcomings of the DMS; but the FMS also has its own shortcomings. The low throughput and high equipment cost due to the redundant flexibility and complexity in the design of FMS are the greatest disadvantages, preventing it from readily replacing DMS. Consequently it is necessary to take into account recent manufacturing strategies, such as reconfigurable manufacturing, to enable the possibility of easy switching between products as situations arise. Reconfigurability in the manufacturing environment is the ability of the manufacturing system to modify its elements (machine tools, material handling systems, assembly workstations, and so forth) rapidly and reliably to accommodate planned or unplanned/sudden changes in product design or specifications without expensive set-up costs or long idle times (shutdown periods).

Reconfigurability has different meanings for different researchers, depending on their perspective on the subject. Lee [6] defines it as the ability of a manufacturing system to be reconfigured at a low cost and in a short period of time. NSF Engineering Research Centre for Reconfigurable Manufacturing Systems defined it as the ability to adjust the production capacity and functionality of a manufacturing system to new circumstances by rearranging or changing the system's components [7]. Wiendahl et al. [8], give another definition: it is the operative ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements. In the view of Setchi and Lagos [9], the essence of reconfigurability is to enable manufacturing responsiveness to a change in market conditions - that is, the ability of the production system to respond to disturbances that may be caused by social or technological changes. In the view of Galan et al. [10], the need for reconfigurability does not necessarily arise solely from the market or customers, but can also emanate from within the company for the sake of relevance. Sometimes a company needs to review its products, to enable them to compete favourably with other similar products in the market. This may call for a reconfigurable manufacturing system. The need for reconfigurability can also be viewed from the perspective of increased customer demand, giving rise to increase in supply. Usually, if this need has to be met, it may be necessary to procure more and/or sophisticated equipment to add to or to replace existing equipment. But if the manufacturing system is not reconfigurable, incorporating this new equipment may pose problems. For example, the old line may have to be condemned and a new one built so that the needs of the current market can be met. However, this may be too expensive and time-consuming, hindering such expansion. An operation might be phased out of the system for lack of reconfigurability for the reason stated above. Lee [6] looked at reconfigurability from this perspective when he classified reconfigurability as either 'classical' or 'dynamic'.

It can be deduced from these different definitions that the major objective of reconfigurability is to achieve "exactly the capacity and functionality required and exactly when needed". Reconfigurability is achieved with six basic characteristics: modularity, scalability, integrability, convertibility, diagnosibility and customisation [5]. Most of the authors researching reconfigurable manufacturing systems ended up recommending manufacturing system reconfigurations such as relocating machine(s), replacing machine(s), adding or bypassing machines and procuring reconfigurable machines where available to build the manufacturing system. Though all of these provisions may aid reconfiguration, it is necessary to look at the feasibility and economy of carrying them out. There are cases where moving the machine(s) is either not feasible or not economical (the action is not commensurate with the profit it will generate); in other words, the machine(s) are immovable. The present work sought to provide a solution to such a situation.

2. LITERATURE REVIEW

Searching through the literature, it was discovered that a great deal of work has been done in the area of reconfigurable machine tools, reconfigurable products, reconfigurable manufacturing cells, reconfigurable process planning, reconfigurable control systems, etc. However, as it is a manufacturing system in terms of the definition given above - i.e., an aggregation of manufacturing elements - authors have not given much attention so far to its reconfigurable form. A literature search revealed that, to the best of the present authors' knowledge, little work has been done in this area. Some work found in the literature that tends towards the subject matter is presented below.

Knowledge of the three manufacturing concepts – the bionic manufacturing system (BMS), the fractal manufacturing system (FrMS), and the holonic manufacturing system (HMS) - is a good motivation for the development of a reconfigurable manufacturing system. Of note is the comparison of these three manufacturing concepts in the work of Tharumarajah et al. [11]. Their work describes the underlying principles on which these manufacturing concepts are based, and also compares their design and operational features. The knowledge gained from these concepts was of immense value in the design/development of the reconfigurable manufacturing system presented in this paper.

In a paper presented by Koren et al. [4], the reconfigurable manufacturing system was presented as aggregating reconfigurable manufacturing elements such as machines, material-handling systems, control systems, measuring devices, etc. However the paper offers a motivation for embracing the new paradigm in manufacturing system design, known as a reconfigurable manufacturing system, and no specific manufacturing system design is presented. The work of Ko et al. [12] is not identified as addressing reconfigurable manufacturing; but from reading the paper it is clear that the work is centred on the reconfigurability of manufacturing. Entitled "Reusability assessment for manufacturing system", it presents different configurations that could aid the future reconfiguration of the manufacturing system.

The issue of reconfiguring a cellular manufacturing system is exhaustively discussed by Saad [13], who introduces a new approach to the reconfiguration of cellular manufacturing systems, using the virtual cells concept. According to Saad [13], a manufacturing system can be reconfigured via a dynamic restructuring process to handle disturbances. Although the dynamic restructuring process is not documented in the literature, the principle is employed in the design and development of the reconfigurable manufacturing system presented in this paper.

The work on reconfigurable manufacturing systems for agile mass customisation manufacturing presented by Xing et al. [14] is similar to that presented by Koren et al. [4] in the sense that different reconfigurable manufacturing elements are highlighted; but how they could be made reconfigurable together as a manufacturing system is not considered.

The work of Bruccoleri et al. [15] focuses on how reconfiguration can be employed to handle any breakdown in the manufacturing system. They considered an approach based on the reconfiguration features (like the ones incorporated in the present work) of reconfigurable manufacturing systems for error handling in scheduling systems. The authors then propose a high-level object-oriented control architecture for error handling, aided by reconfiguration, and present it by using the unified modelling language notation. Singh et al. [5] evaluated the existing (DMS and FMS) and new generation manufacturing systems (HMS and RMS) by trading off among the tangible and intangible design parameters. This evaluation was carried out by using the analytical hierarchy process (AHP). They showed that, in the long-term, existing manufacturing systems have to be replaced by a reconfigurable manufacturing system so that they can cope with increasing product variety and uncertainty in market demands in volume and variety.

The concept of mobile manufacturing is described as an aid to reconfiguring a manufacturing system in the work of Stillström and Jackson [16]. Using their definition of mobility in a manufacturing system as its ability to switch effortlessly and quickly between products, they show that the concept is similar to that of reconfigurability. In their work, the concept of mobile manufacturing is analysed by describing five demonstrators in the factory-in-a-box research project. The design of a manufacturing system in accordance with demonstrator 1 and 3 (i.e. a mobile and reconfigurable robot cell, and a mobile robot cell for foundry application) will make it fully reconfigurable within a short period and at comparatively little cost. The problem with most designs for reconfigurable manufacturing systems is the requirement that the manufacturing elements should be mobile. In fact, the work described in this paper is a response to making a manufacturing system reconfigurable without the characteristic of manufacturing system mobility.

3. PROPOSED DESIGN AND DEVELOPMENT OF RECONFIGURABLE MANUFACTURING SYSTEM FOR A SITUATION WHERE THE WORKSTATIONS ARE ECONOMICALLY RIGID (IMMOVABLE)

The design process for a manufacturing system can be broken down into the following phases:

- Layout design — which includes the choice of machines and layout of the manufacturing system.
- Material-handling system design/selection — which includes the choice of material-handling equipment.
- Control system specification — which includes the choice or specification of the control scheme.

The goals of this paper are to choose or design a suitable layout for the workstations, to arrange a material-handling system in a way that facilitates the reconfigurability of the manufacturing system without necessarily changing the position of workstations, and to specify the control system needed to help the manufacturing system to work effectively.

3.1 Layout design

The problem of facilities layout deals with assigning *m* facilities to *n* locations ($m \leq n$), in such a way that the sum of the fixed investment (or installation costs) and the sum of associated material-handling costs are minimised [17]. Line layout is usually determined by the type of material-handling system employed [18, 19], but research has shown that U-shape line layout offers several benefits, especially in improving the productivity of labour, over the traditional straight-line layouts [20]. This is one of the reasons for the choice of a U-shaped line layout for the workstations in the proposed manufacturing system design. Another reason is that it favours the technique employed for the reconfiguration of the manufacturing system.

The proposed design is basically a dedicated manufacturing system that is made reconfigurable by the provision of some extra material-handling system, between all the workstations, and an auxiliary buffer within which a reconfigurable control system is incorporated. The auxiliary buffer was introduced to prevent the extra/auxiliary material-handling systems from intercepting one another during the manufacturing system reconfiguration.

3.2. Material-handling system design/selection

The task of the design/selection of the material-handling system (MHS) consists of determining the material-handling system to be used, calculating the unit loads or batch size for the MHS, assigning specific material-handling equipment to departmental moves, and developing the flow path for the system [21]. The choice of material-handling devices is dependent on the following factors: the size of the company, the nature of the operations that will be performed on the manufacturing system, the available space, and the functional requirements of the manufacturing system. For the work reported in this paper, the manufacturing system is part of a whole manufacturing system (a manufacturing cell). The functional requirement is to make the manufacturing system reconfigurable; a machining operation is assumed to be the operation for which it is intended; the available space is also assumed to be limited, although this factor has been taken care of by layout design. Therefore the appropriate MHS is one that will be able to pick up and deliver material between two workstations. Although a conveyor could serve this purpose, it should be a segmented conveyor and not continuous - in other words, it will be located between each of the workstations and appropriately between the workstations and the auxiliary buffer (as shown in Figure 2) to aid reconfiguration. Also appropriate to the current design is the automated guided vehicle (AGV). AGVs by design are pre-programmed trucks controlled through a central computer; they travel a predetermined route and stop at a designated workstation (machine or measuring/marking or inspection centre) where the material is either picked up or dropped manually, or this is done by other automated material transfer devices. It is important at this point to mention that, for the purpose of reconfigurability and in accordance with the machine relocation rule 1 (which emphasises the use of bidirectional material-handling carriers) as presented by Lee [6], all the material-handling carriers should be bidirectional. This is the basic design criterion that takes care of possible workstation relocation.

A material-handling system is a key component of any manufacturing system, as its cost accounts for 40% or more of the total cost in an average factory [22, 23]. The cost of the MHS will definitely be higher in the case of the proposed reconfigurable manufacturing system because it is the key aid to the manufacturing system's reconfigurability.

3.3 Control system specification

The auxiliary material-handling system provided for reconfiguration makes the control system of the proposed manufacturing system more complex than the corresponding dedicated or flexible manufacturing system. Apart from the interrelationship between workstations, machines in the workstations, components, tooling, and personnel, the co-ordination at the auxiliary buffer of the direction of the material-handling system, and the acceptance and delivery of work-in-progress from one material-handling system to another as dictated by the route sheet of the job at hand, may be challenging. The approach to this challenge is to break the control into its hierarchical levels, where each level of the hierarchy has a narrower responsibility [23]. A number of hierarchical control systems have been developed for manufacturing systems and can be found in the literature. An ideal control system for the proposed RMS is similar to those presented by Costa and Garetti [24] and the database model of Lin and Fang [25]. A control system that meets the requirements of the job shop production of a flexible manufacturing cell (FMC) in their works, plus the additional requirement at the auxiliary buffer of the proposed RMS model shown in Figure 2, would be appropriate. The control system at the auxiliary buffer is expected to control the direction of the material-handling system and to co-ordinate the acceptance and delivery of work-in-progress from one material-handling system to another, as dictated by the route sheet of the job at hand. With adequate scheduling, the control system at the buffer can be programmed on the basis of the algorithm presented in Figure 5.

3.3.1. Control at the auxiliary buffer

Ease of control at this buffer requires the proper scheduling of operations at all the workstations and the material-handling system. There are two ways of performing the control identified in this work: either the buffer is in the form of a rotary table, or a robot palm serves as the buffer. For a reconfigurable manufacturing system where the auxiliary buffer is engaged, the time it will take the workpiece to undergo its operation at the workstations and to travel through the MHS prior to its delivery to the buffer is needed. So scheduling must be carried out that takes into account the route a part must take through the system and the time associated with travel and the processing of the part. The rotary table buffer will be set to rotate through angle θ (the angle between the MHS that is delivering the workpiece and the MHS that is meant to receive the workpiece) after the workpiece has been dropped on it, and then to deliver it to the appropriate MHS for onward delivery to the next workstation. In this way, by calculating the time that a workpiece will spend in all the workstations for its operation before engaging the auxiliary buffer, its rotation can be pre-programmed for the machining period of the workpiece. Similarly, if a robot is used, the robot will be pre-programmed to turn through angle θ and deliver the workpiece to the next MHS after the time has elapsed that the workpiece was supposed to spend at the workstation and the travelling time on the MHS prior to delivery on to its palm.

To facilitate book-keeping at the buffer, each work-in-progress has to be tagged (i.e. given a unique identification code). The reason is that, once operation has started, there may be more than one work-in-progress in the manufacturing system, and therefore a pool of them in the auxiliary buffer. The design of a control system is really beyond the scope of the present work, but the idea stated above is a suggestion and recommendation for further work by experts in the software and control field.

Alternatively, the auxiliary buffer can be manned by a human operator to co-ordinate effectively the acceptance and delivery of work-in-progress from one material-handling system to another, as dictated by the route sheet of the job at hand. For the MHSs that connect the workstations and auxiliary buffer, the direction is supposed to be determined before the start of operations, based on the process plan. Figure 1 shows a sketch of a control system at the auxiliary buffer, using a rotary table as the buffer.

Figure 2 shows the model of the proposed manufacturing system. This represents the arrangement of the machines/workstations in each manufacturing cell that make up the entire manufacturing system. It comprises eleven workstations. A workstation may be a machining station, a measuring/inspection station, a cleaning/washing station, or an area designated for any other specific operation. It also consists of 21 material-handling systems: ten connect the workstations to one another, and eleven connect each of the workstations to the auxiliary buffer located at a suitable position to optimise the distance to be covered by the material-handling systems during operation.

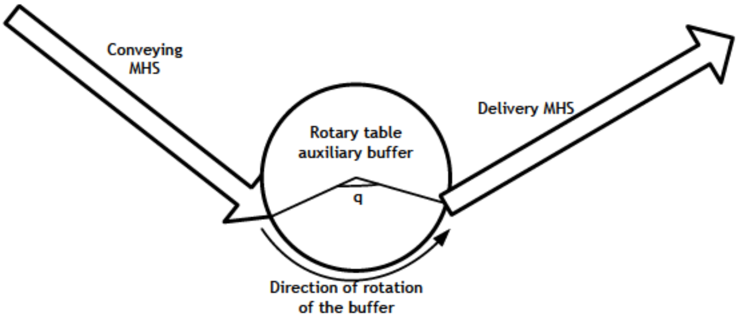

Figure 1: An iconic representation of suggested control method at the auxiliary buffer

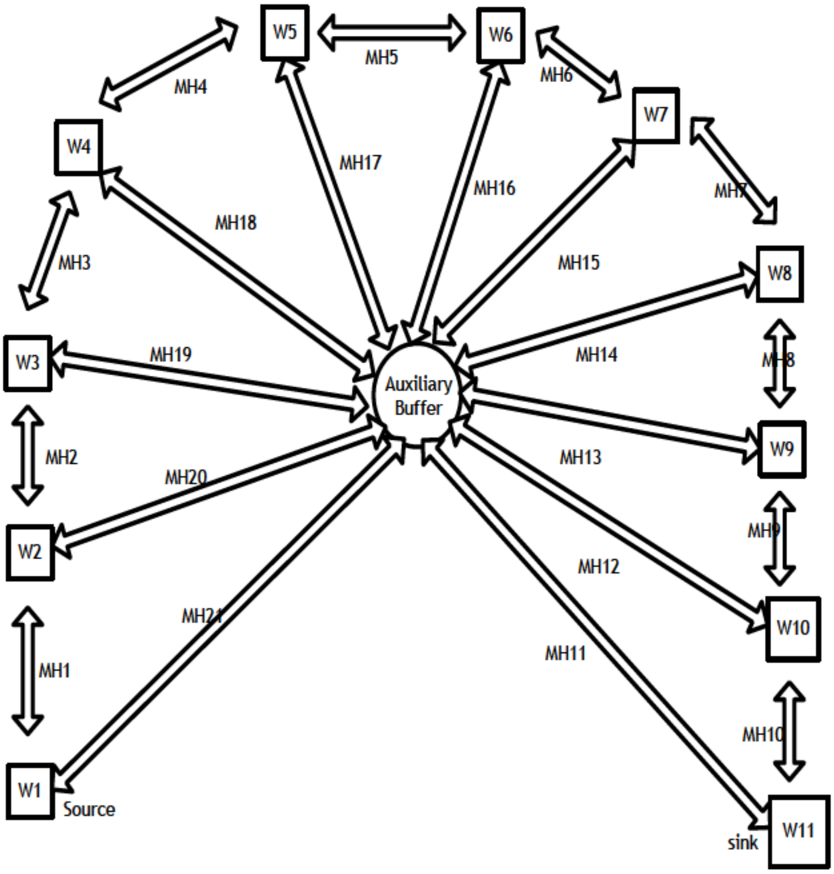

Figure 2: Proposed reconfigurable manufacturing system

The manufacturing system designed for the initial product is the U-shaped manufacturing system of workstations W1 to W11. This manufacturing system has the workstations arranged according to the route sheet of the initial product to be manufactured. It is a form of dedicated manufacturing system where the cost of moving workstations from their positions is too high. Material-handling systems MH11 to MH21 are actually redundant until the need for a reconfiguration of the manufacturing system is occasioned by a change in the product or otherwise. It is important to mention that all the material-handling systems must be bidirectional because reconfiguration may require that they move in either direction, as will be shown in this example. Assume that the manufacturing of a new product will require an arrangement of workstations in the following order: W1-W2-W4-W3-W8-W9-W6-W5-W10-W11. Then the material-handling MH20, MH18, MH19, MH14, MH13, MH16, MH17 and MH12 will have to be activated while others are de-activated. It is not necessary that the material-handling systems be in place when they are not needed; but this has to be provided from the onset of the design and development of the manufacturing system. It is this provision that differentiates a pure dedicated manufacturing system from a reconfigurable manufacturing system. In the above example, the original manufacturing system has the workstations arranged as follows (i.e. the U shape): W1-MH1-W2-MH2-W3-MH3-W4-MH4-W5-MH5-W6-MH6-W7-MH7-W8-MH8-W9-MH9-W10-MH10-W11, as shown in Figure 3.

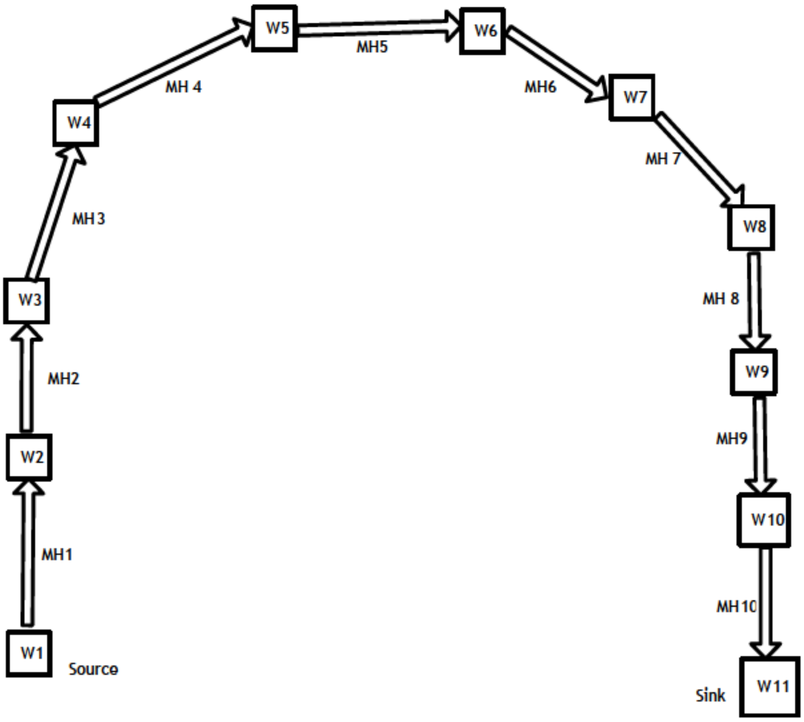

Figure 3: Original/Initial manufacturing system with provision for material-handling system (MH11-MH21) not displayed but available in the system for activation when necessary.

Figure 3 shows the layout of the manufacturing system before reconfiguration, with the direction of the material-handling system clearly indicated.

Based on the proposed manufacturing system in Figure 3, Figure 4 shows a reconfigurable manufacturing system algorithm that can give rise to a reconfigured manufacturing system such as the one shown in Figure 5. The algorithm does not include the flow inside the buffer, as this would make the algorithm too complex. The flow of work in the buffer is therefore shown separately in Figure 6.

The reconfigured manufacturing system based on the route sheet of the example given above, and following the algorithm in Figure 4, will no longer be U-shaped but will have a serpentine layout [18] as follows: W1-MH1-W2-MH20-MH18-W4-MH3-W3-MH19-MH14-W8-MH8-W9-MH13-MH16-W6-MH5-W5-MH17-MH12-W10-MH10-W11. The layout is shown in Figure 5. In this way, different products may be produced in whatever quantity at any point in time with a minimum lead time. The required set-up time is the time needed to adjust the control of the material-handling systems to activate them, and also to mount them in case they are not in position.

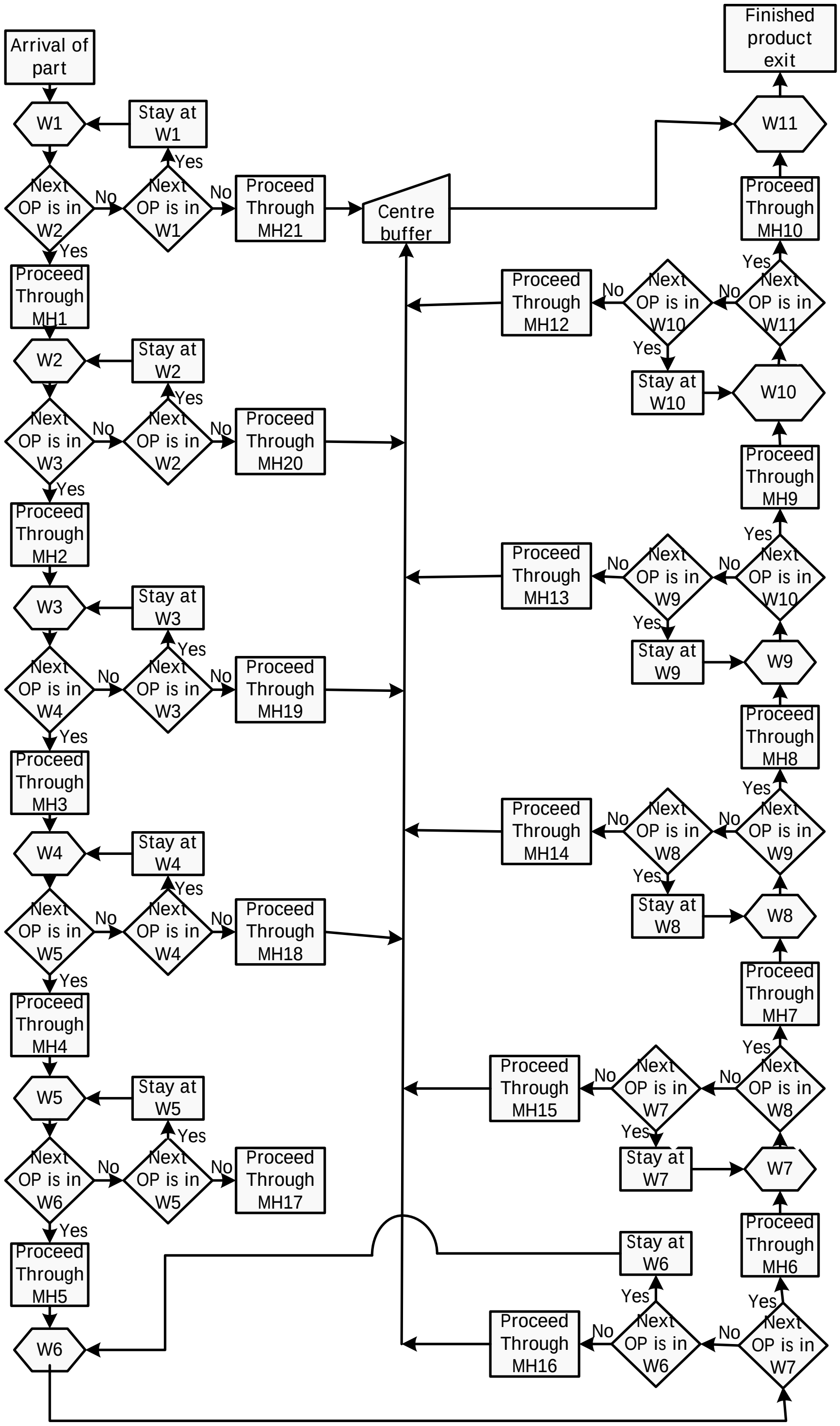

Figure 4: Flow chart for the designed reconfigurable manufacturing system - outside the auxiliary buffer

Legend: OP = Operation, MH = Material-handling device, W = Workstation (Machine, Measuring table, cleaning device, etc.)

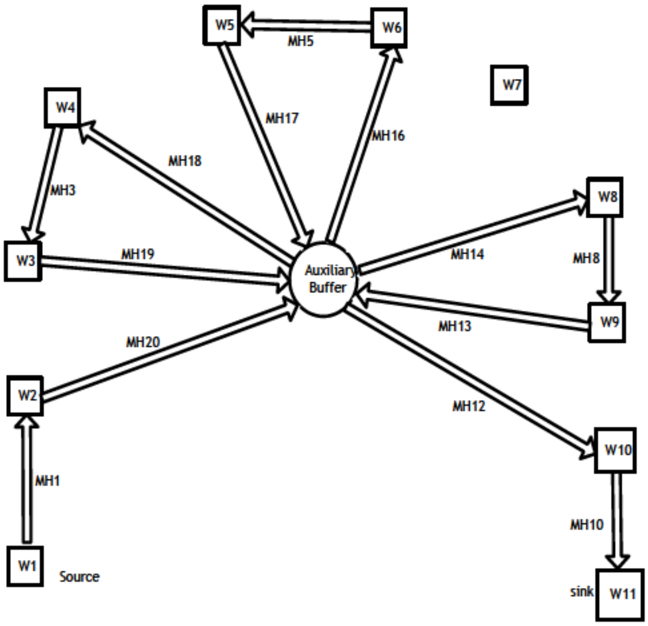

Figure 5: Reconfigured manufacturing system

The algorithm shown in Figure 6 represents the flow of a workpiece at the auxiliary buffer of the manufacturing system in Figure 5.

According to Koren et al. [4], a reconfigurable manufacturing system can be reconfigured at three levels: (i) system level (e.g. changing the layout reconfiguration), (ii) machine level (e.g. adding a new spindle or replacing any other components of a machine), and (iii) control level (integrating a new software module). In the proposed manufacturing system, it is possible to carry out all of these levels of reconfiguration without necessarily having to move the workstations from their original position. This will save time and cost, particularly when it is not economically feasible to move the workstations.

4. CONCLUSION

The proposed RMS exhibits the six basic characteristics of RMS highlighted by Singh et al. [5] and other authors. The ability to disable some MHSs and enable others at will shows that a modularity property is exhibited. The fact that a number of workstations can be put to use while others are kept out of use as dictated by the operation at hand, is a fulfilment of the scalability property. The original dedicated manufacturing system is integrated with some manufacturing system element (MHS) in its reconfiguration in order to convert it into a new manufacturing system, which is proof of its integrability and convertibility. The proper choice of a control system will aid the diagnosibility property; and the ability to switch from the production of one product to another, as shown in this paper, is an indication of customised flexibility.

The proposed reconfigurable manufacturing system addresses the problem that usually arises when there is a need to change the position of workstations (machine and other manufacturing facilities) in order to accommodate a change in product, when the cost of doing so is much higher than the benefits this will achieve. The only additional cost of the proposed reconfigurable manufacturing system, compared with an equivalent dedicated manufacturing system, is the cost of installing extra material-handling systems (MHS12 to MHS20) and, once this cost has been incurred at the inception of the manufacturing system, it will enable the reconfiguration of the manufacturing system as many times as needed.

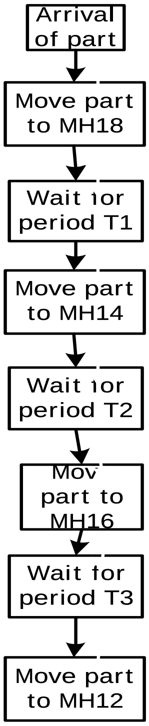

Figure 6: Flow chart for the auxiliary buffer

Legend: MH = Material-handling device, T1 = Time spent on performing the operation at W3 and W4 + Time spent on MH 18, MH3 and MH19; T2 = Time spent on performing the operation at W8 and W9 + Time spent on MH 14, MH8 and MH13; T3 = Time spent on performing the operation at W5 and W6 + Time spent on MH16, MH5 and MH17.

5. LIMITATION OF THE RESEARCH

The designed RMS is suitable for products requiring the same workstations (machines and other equipment) for their processing, or for products that require fewer workstations than the product for which the manufacturing system was originally designed but in a different order of precedence. Usually, in products such as moulds and dies, there are common features to be fabricated, but because only the position and size differ from one product to another, the same type of equipment is repeatedly required to create these features in a different order. The designed reconfigurable manufacturing system is therefore suitable for the production of moulds and dies and similar products.

6. RECOMMENDATION ON FURTHER WORK

Further work should be done on the control at the auxiliary buffer. The control system at the auxiliary buffer is expected to control the direction of the material-handling system and to co-ordinate the acceptance and delivery of work-in-progress from one material-handling system to another, as shown on the route sheet of the job at hand. More work should be done on the control idea presented above.

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