Design and Simulation Based Validation of a Reconfigurable Manufacturing System

Bashir Salah
Industrial Engineering Department, College of Engineering, King Saud University,
Advanced Manufacturing Institute
P.O. Box 800, 11421, Riyadh, Saudi Arabia
bsalah@ksu.edu.sa

Abstract

The manufacturing industry has a high potential of being exposed to continuous market changes that need to adapt successfully to a rapidly changing market environment. Therefore, the ability to cope with these factors is vital. Reconfigurable Manufacturing Systems (RMS) have a cost-effective response to rapid changes, as well as have the capability to cope with market changes (due to the variation in customer and supplier behaviors) by adapting to various manufacturing systems. In this paper the authors present a method to assess and choose the appropriate manufacturing design layout. Three different configurations have been designed using the CAD program SOLIDWORKS; the configurations were compared using ARENA 14.7 simulation software to simulate the process of manufacturing a product. The configurations were then evaluated using various performance measures, including resource utilization, waiting time and throughput. The evaluation was used to identify the appropriate configuration design. The results show that the proposed methodology can offer a suitable configuration that can achieve high performance as well as adapt to market changes.

Keywords
Reconfigurable Manufacturing Systems, RMS configuration, Simulation.

1. Introduction

Manufacturing companies are often subjected to different factors that can impart rapid changes to their manufacturing systems. Therefore, the ability to cope with these factors is vital. Such companies should possess manufacturing facilities that can respond quickly and in a cost-effective manner to market changes. Reconfigurable Manufacturing Systems (RMS), whose components include reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and rapid ramp-up, are the foundations of this new manufacturing paradigm (Koren et al., 1999).
A Reconfigurable Manufacturing System has the high capability of adapting to rapid or un-predictable market changes in a cost-effective way. RMS can integrate the features of the two types of manufacturing systems, Dedicated Manufacturing Systems (DMS) and Flexible Manufacturing Systems (FMS), thereby achieving high productivity, a changeable system structure, and a medium cost (Koren et al., 2006).
In the next sub-sections, the authors first discuss some recent research relevant to advances, designs, and evaluation of various types of manufacturing systems. This is followed by problem statement and highlight of the RMS problem that has been addressed by the authors in this manuscript.

1.1 Background

Koren (2010) demonstrated that products have a life cycle. When the life cycle is over, a new product appears which, consequently, requires a new manufacturing system. A new manufacturing system requires a high initial investment cost. Therefore, the implementation of a new manufacturing system for each product is usually not an effective

solution. A better solution that can save money and effort is to design and build a manufacturing system that takes the evolution of products into account.

(YÜCEL 2005) used ARENA to build a simulation model for a Flexible Manufacturing Cell consisting of a CNC milling machine, CNC lathe machine, an automated guided vehicle (AGV), a conveyor and robot. The simulation model was tested using different scenarios such as first come first served (FCFS), earliest due date, priority, longest and shortest process times. The results were then analyzed using selected performance measures in order to determine the best scenario for the selected Flexible Manufacturing Cell. The study provides a proposal for an effective use of simulation in manufacturing systems.

Liraviasl (2015) illustrates simulation modelling techniques such as discrete-event, system dynamics, and agent-based techniques. Such techniques provide beneficial functional requirements that can be used to build the desired production line. In addition, simulation software decreases the risk of failure for examining new planning and control methods in production lines. Most of the effective evaluation processes for RMS use the afore-mentioned RMS core characteristics to measure performance levels. With the use of ARENA simulation software as an additional source of evaluation, this makes the examination more accurate and precise. It also provides new performance indicators that can be used to evaluate the system.

Wang (2012) used the RMS chore characteristics of Modularity, Integrability, Customization, Convertibility, Diagnosability and Scalability to evaluate the manufacturing system that was implemented in The Lego Group. They used different evaluation criteria to rate the different characteristics and determine the most relevant for RMS.

A recent article by Koren (2016) provides principals to designers of modern manufacturing systems using the throughput of scalability of reconfigurable manufacturing systems. This is expected to enable companies to possess a manufacturing system that is able to respond to market demands in a timely, cost-effective manner, as well as upgrade its throughput in the future.

1.2 Proposed RMS Tool

In this article, the authors introduce a new manufacturing design and simulation based tool based on a RMS. This RMS is designed to have a cost-effective response to rapid changes, as well as an improved capability to respond to market changes. This may contribute to reducing the production cost and allowing faster moving of products to the market.

Three different design configurations are compared using the proposed RMS. A methodology is developed to identify a suitable configuration to achieve high performance as well as complying with unpredictable changes. The configurations were designed using the CAD design software SOLIDWORKS and simulated using ARENA 14.7 simulation software. The configurations were then evaluated using five performance measures which are throughput, total time in system, resource utilization, queue length, and queue waiting time. Finally, the evaluation was used to identify the appropriate configuration design. The results show that the proposed methodology can offer different configurations that may achieve high performance, as well as the ability to adapt to market changes.

In the upcoming section, we elaborate on steps used to validate the suggested designed configurations using simulation software specifically developed for this purpose.

2. Methodology and model development

2.1   Research Methodology

Manufacturing systems could be designed in different configurations; however, different configurations have different efficiencies at different production levels. In order to identify the suitable configuration, an evaluation of performance for each configuration is required to identify the appropriate design layout. In this paper, evaluation and comparison of each configuration is introduced via ARENA simulation software in order to identify the number of performance measures.

We start by identifying the product which has to be produced. The manufacturing processes are identified according to the created routing sheet. The processes are then used to determine the resources. Subsequently, the configuration models are designed for comparison. Finally, simulation models are developed and the results are collected for analysis. The most effective design layout configuration is then selected according to the selected performance measures. Figure 1 illustrates the proposed research methodology that has been developed.
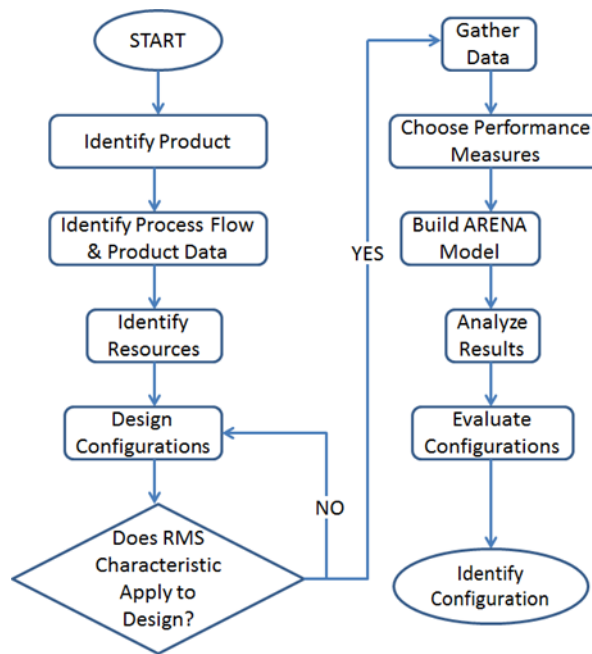
Figure 1. Research methodology flowchart

2.2   Product Description

The product chosen for evaluating the proposed configuration layout is shown in Figure 2. The selected product consists of three parts, two of which are identical (the lower and upper cap), and a cylinder part.
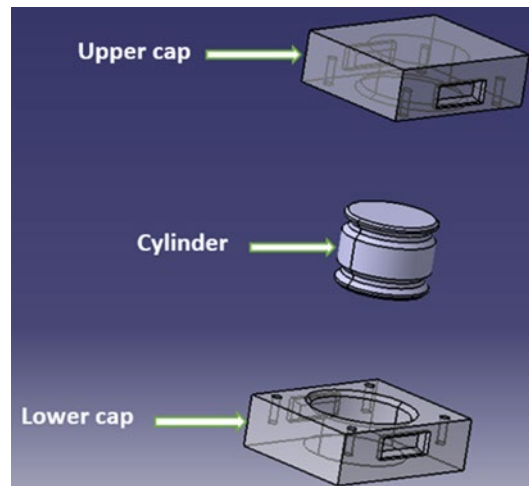

Figure 1. CAD model for the proposed product

2.3   Routing sheet

The product mentioned in the previous section was designed with the CAD software tool CATIA. Appropriate tools and parameters were inserted in the software in order to calculate the process time for each manufacturing process. Table 1 represents the routing sheet for the chosen product.

Table 1. Routing sheet

#	Operation Description	Machine	Tool	Machin-ing Time (min)	Loading/ Unloading Time (min) U-Shape	Loading/ Unloading Time (min) O & L-Shapes
1	Cap: Milling on the two sides, depth: 3.5 mm	Milling machine	End Mill, Diameter 4	1.35	0.3	0.4
2	Cap: Milling in the center, depth: 17 mm	Milling machine	End Mill, Diameter 20	3.61	0.3	0.4
3	Cap: Drill 4 holes, depth: 10 mm	Drilling machine	Drill Diameter 4	1.51	0.3	0.4
4	Cylinder: Turning, depth: 4 mm	Lathe machine	Taper Turning	6.3	0.3	0.4
5	Assemble final product	Robot		0.5	0.3	0.4

2.4   RMS Configurations and Assumptions

This study was designed to compare the effectiveness of three alternative structural configurations for a manufacturing system. The configurations were designed based on the number of machines and robots needed to manufacture the proposed product. After identifying the required machines and robots, the distances between machines were determined. Additionally, the safety distance between each two successive machines was assumed to be one meter. In addition, an infinite buffer is assumed to exist in front of each cell for the storage of parts waiting to be processed.

Another factor that affects the design of the configurations is the placement of robotic arms. The robotic arms are either placed inside the configurations (if such is possible); otherwise, they are placed on the outer side of the configuration, if there is no space for them to be placed inside.

The three alternative structural configurations for manufacturing systems are presented in the following sub-sections.

2.4.1   L-Shape Configuration

The L-Shape configuration has some constraints regarding the belt conveyor which has to be used due to the corner in the "L-shape", as shown in Figure 3 and Figure 4. In addition, since there is no space for the robotic arms to be placed between the conveyors, and, consequently, the robots are placed on the outer side of the conveyors. One of the advantages of this system is it has a closed loop conveyor.
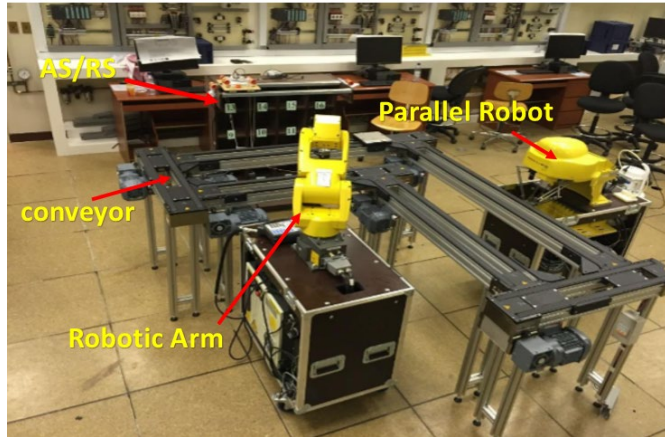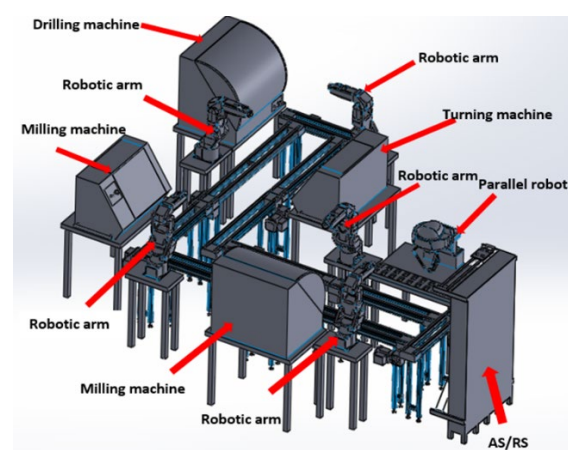
Figure 2. L-Shape Configuration

Figure 3. L-Shape Configuration, CAD model

2.4.2 U-Shape Configuration

This configuration has a unique advantage, as opposed to the other configurations, whereby it has the ability to place the robotic arm between conveyors, as shown in Figure 5 and Figure 6. With the placement of the robotic arms between the conveyors, the length of the overall conveyors is reduced. As a result, reducing the length reduces the transportation time between machines and the overall time from first entering the system to exiting. The configuration is an open loop configuration, which indicates that the conveyor starts from one point and ends at another point.
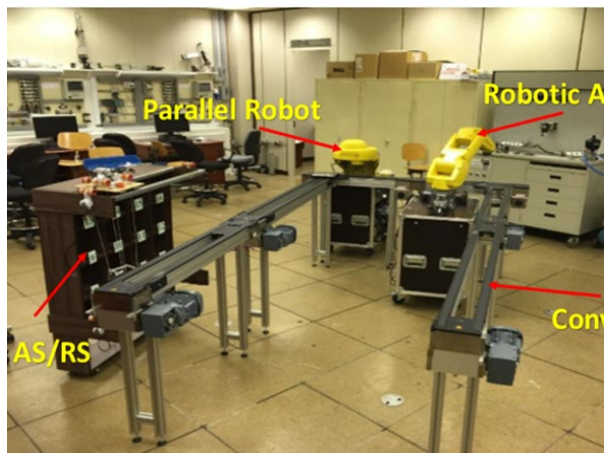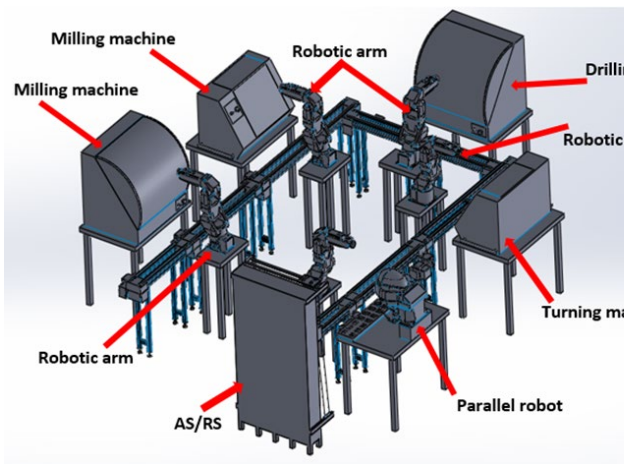

Figure 4. U-Shape Configuration

Figure 5. U-Shape Configuration, CAD Model

2.4.3 O-Shape Configuration

As opposed to the "L-shape" configuration, this configuration has the no sufficient space between the conveyors. It, therefore, requires more conveyors to allow placement of the robotic arms. Like the "L-shape" configuration, this is a closed loop configuration (see Figure 6 and Figure 7).
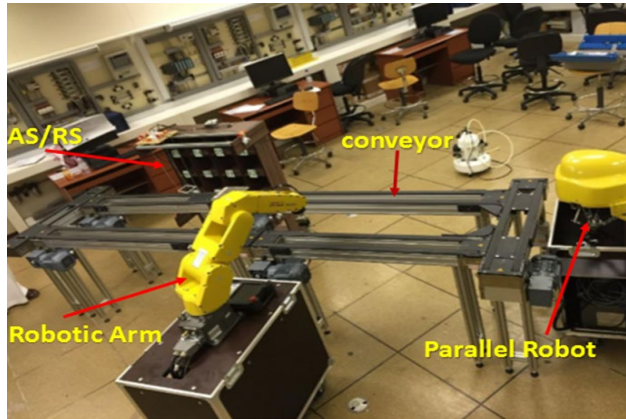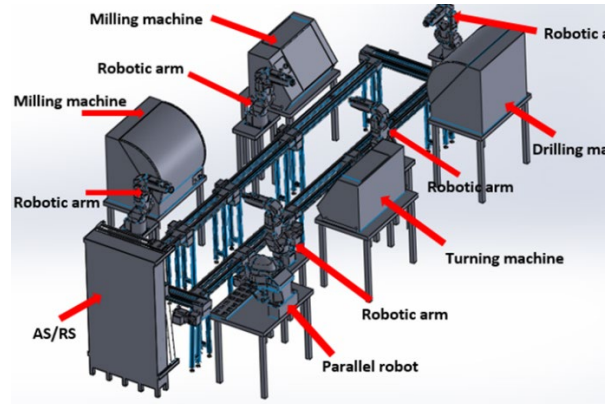
Figure 6. O-Shape Configuration

Figure 6. O-Shape Configuration, CAD Model

3. Simulation and performance evaluation of RMS

The manufacturing industry has made various studies on how to cope with change and uncertainty in the market. One of these studies demonstrates the use of a simulation tool to demonstrate the manufacturing system's behavior (Khedri et al., 2015)

In the current study, ARENA 14.7 is used to simulate the three designed manufacturing systems. When simulating a manufacturing system it is essential to identify entities, attributes, variables, and resources for a proper representation of the system, which is discussed below.

In any system, pinpointing entities is one of the most important aspects in the system. Entities are the dynamic objects in the simulation model. They move around the system and change status by affecting or being affected by other entities. Entities are considered as the essential element in the simulation (Kelton, et al. 2010). In manufacturing systems, a simple example of an entity is the part to be produced.

In the current model, two entities are created which are the cap and cylinder. The final process involves a new entity which appears as the final product, consisting of two caps and one cylinder.

The attributes provide entities with a unique identification. This is a common characteristic for all entities, yet, with different values assigned to each entity. The value may be as-signed or changed at any time during the simulation run. The list of attributes used in the simulation model and their brief purpose of usage in the developed models is provided in Table 2.

Table 2. List of Attributes

Name of Attribute	Description
Part index	Each entity is given a unique index in this attribute
Process time	The time for each process is assigned to this attribute
Put together	Common attribute to batch the cap with the cylinder
Entity.picture	The pictures used in the animation are assigned to this attribute
Entity.sequence	The entity follows the sequence defined in this attribute
Entity.type	The part types are assigned to this attribute

The difference between variables and attributes is that variables are characteristics that affect the whole system. There are two types of variables, ARENA variables, and user-defined variables. ARENA variables are those that were created by the program itself, e.g. number of parts exiting the system. On the other hand, user-defined variables are variables that are created by the user. The user-defined variables for the simulation model are described in Table 3.

Table 3. List of Variables

Name of variable	Description
Load Time	Time to load the part onto the conveyer
Unload Time	Time to unload the part from the conveyer

Resources are the services that are provided to the entities. The entity first seizes a place in the resource then releases it after the required operation is complete. A resource can include many services. In manufacturing systems, a resource usually represents a machine or personnel. In our system, six resources are used for the process operation. They have a fixed capacity of one part to serve. The resources with their names and types are listed in Table 4.

Table 4. List of Resources

Name of resource	Type
1. Milling	Machine
2. Milling 2	Machine
3. Drilling	Machine
4. Turning	Machine
5. Assembly	Robot
6. AS/RS	Storage system

In addition, two non-operation resources have been used in the system. First is the (serial and parallel) manipulator arm, which is used to load/unload the part from/onto the conveyer. Second is the conveyor, which is used to transport parts between stations. The distances between stations are called segments. In our system a segment represents the distance between the robotic arms.

4. Results

The results of the three different configurations were analyzed as follows. The configurations were evaluated according to performance measures that represent the design of the configuration. The simulation time for the configurations was based on 8 hours of operation.
The performance of the system is divided into two aspects, overall system performance, and resource performance. First, overall system performance is divided into throughput and total time in the system. The resource performance is divided into resource utilization, queue length, and queue waiting time.
An overall performance measures results of the three designed CAD models, which is shown in Table 5.

Table 5. Overall Performance Results.

Configuration	Through-put	Avg. Total Time in System	Avg. Resource Utilization	Avg. Queue Length	Avg. Queue Time
	Units	Min.	%	Units	Min.
L-Shape	62	91.97	58.65	4.14	19.6
U-Shape	63	80.52	59.19	4.25	19.79
O-Shape	62	89.87	58.746	4.08	19.24

Table 5 points out that the U-shape has the highest throughput, least amount of time in the system, and the highest resource utilization rate. Although it also has the highest queue length and waiting time, it still remains favorable as throughput and utilization rates are considered primary factors.

5. Conclusion

Designing a manufacturing system that can cope with changes rapidly and precisely is a major objective for companies.
This paper presents a methodology to identify a manufacturing system that can handle different changes in the market environment. The evaluation and identification process mainly consists of a simulation model that can provide different performance measures that enable choosing a suitable configuration.
A methodology was developed here to find a manufacturing system aimed at coping with changes in a precise manner as well achieving high performance. Three configuration designs were used as alternatives to determine which configuration was most suitable using the developed methodology.
The three configurations were evaluated via ARENA simulation software. Several types of data were collected regarding the product and configurations. The collected data were used to evaluate the performance of each configuration and consequently choosing the most suitable configuration.

6. Acknowledgment

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Biography

Bashir Salah Vice Dean of Advanced Manufacturing Institute. Since March 2014 Dr. Salah works as assistant professor of industrial engineering at king Saud University, KSA. His job involves conducting research as well as teaching undergraduate courses in the area of industrial engineering. Furthermore, he is involved in several administrative duties in the Industrial Engineering Department. He is also a member of accreditation committee in the same department. Dr. Salah has established collaborations in a wide range of industrial and academic projects, at both national and international levels. His current research interests lie in three areas: (i) design and analysis of computer integrated manufacturing, logistics, and supply chain, (ii) industrial facilities planning, and (iii) Industry 4.0, Smart Manufacturing Systems/ Smart Factories. . Dr. Salah received both his PhD and MSc degrees in Industrial Engineering from University of Duisburg Essen, Germany, in 2013 and 2008, respectively. He also attended a professional technical training in mechatronics at the German Technical Cooperation Agency. Before that, he obtained his Bachelor degree in mechanical engineering from Palestine polytechnic university.