Design, Implementation and Evaluation of a Novel Agent-based Control System to Improve Performance of Small and Medium Sized Enterprises: An Industry 4.0 Adoption

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ABSTRACT

Small and Medium-sized Enterprises (SMEs) play a vital role in the world economic structure due to their significant contribution to production, exports and employment. However, there are various financial, marketing and production issues associated with SMEs. This is mainly due to weak traditional manufacturing systems and inflexible control architectures to respond to various market needs. In order to survive, SMEs must be able to overcome the rapid change of the markets and the diverse demands of customers. This involves achieving and maintaining high levels of productivity and the capability to respond rapidly and flexibly in a short lead time.

The Industry 4.0 is a current manufacturing trend which improves efficiency, flexibility and agility, and increases the profitability of enterprises by offering different manufacturing paradigms. However, SMEs' leaders have doubted the benefits of Industry 4.0 for implementation to their manufacturing system. One of the primary design principles of Industry 4.0 is "Decentralized Decisions" which potentially can address the problem of traditional control architecture if implemented. Therefore, this thesis was set out to implement "Decentralized Decisions" to facilitate the Industry 4.0 adoption and improve the efficiency of SMEs. Consequently, a distributed control system was required which was achieved by developing an agent-based control architecture with a Master-Slave mechanism.

Lean Six Sigma (LSS) approach was utilized to recognize the limitations, assess, and maximize the system performance after implementing the developed control architecture. It was achieved by measuring the system production time using a time study technique that is used in performance evaluation which is based on Overall Equipment Effectiveness (OEE). A series of solutions were obtained and applied to a system simulation model to assess their influence on maximizing the performance.

Since the OEE calculation is based on production time which is proportional to distance between the resources and speed, the corresponding solutions were chosen accordingly. The behavior of the resources in system was different for each solution. Therefore, the solutions were prioritized based on their influence on OEE percentage. The OEE percentage improvements varied from 1% to 15% between the resources. It was observed that considering the highest solution priority for each resource results in maximum system performance.

The target system for this research shared the characteristics and features of a SME and the results indicated that implementing the agent-based control architecture along with LSS improved the performance. Implementing both techniques provides a significant step towards successful SME adoption of Industry 4.0 and improves their response to the challenging market.

Keywords: Small and Medium Sized Enterprises, Industry 4.0, Agent-based control, Lean Six Sigma, Time Study, Overall Equipment Effectiveness, Simulation Manufacturing Performance measurement

ÖZ

Küçük ve Orta Büyüklükteki İşletmeler (SME'ler) üretim, ihracat ve istihdama önemli katkıları nedeniyle dünya ekonomik yapısında hayati bir rol oynamaktadır. Ancak, SME'lerle ilgili çeşitli finansal, pazarlama ve üretim sorunları bulunmaktadır. Bu, temel olarak zayıf geleneksel üretim sistemlerinden ve çeşitli pazar ihtiyaçlarına cevap vermek için esnek olmayan kontrol mimarilerinden kaynaklanmaktadır. SME'lerin hayatta kalabilmeleri için pazarlardaki hızlı değişimin ve müşterilerin farklı taleplerinin üstesinden gelebilmeleri gerekir. Bu, yüksek verimlilik seviyelerinin elde edilmesini ve sürdürülmesini ve kısa teslim sürelerinde hızlı ve esnek bir şekilde yanıt verebilmeyi içerir.

Endüstri 4.0 verimliliği, esnekliği ve çevikliği geliştiren ve farklı üretim paradigmaları sunarak işletmelerin karlılığını artıran mevcut bir üretim trendidir. Bununla birlikte, SME'lerin liderleri, Endüstri 4.0'ın imalat sistemlerine uygulanmasındaki faydalarından şüphe ettiler. Endüstri 4.0'ın ana tasarım ilkelerinden biri, uygulandığında geleneksel kontrol mimarisi sorununu ele alabilecek "Merkezi Olmayan Kararlar" dır. Bu nedenle, bu tez, Endüstri 4.0'ın benimsenmesini kolaylaştırmak ve SME'lerin verimliliğini artırmak için "Merkezi Olmayan Kararlar" uygulamak üzere düzenlenmiştir. Sonuç olarak, Master-Slave mekanizmalı bir ajan bazlı kontrol mimarisi geliştirilerek elde edilen dağıtılmış bir kontrol sistemi gerekli olmuştur.

Gelişmiş kontrol mimarisini uyguladıktan sonra sınırlamaları tanımak, değerlendirmek ve sistem performansını en üst düzeye çıkarmak için Lean Six Sigma

(LSS) yaklaşımı kullanılmıştır. Genel Ekipman Verimliliği'ne (OEE) dayanan performans değerlendirmesinde kullanılan bir zaman etüdü tekniği kullanılarak sistem üretim zamanı ölçülerek elde edildi. Performansı maksimize etme üzerindeki etkilerini değerlendirmek için bir dizi simülasyon elde edildi ve bir sistem simülasyon modeline uygulandı.

OEE hesaplaması, kaynaklar ve hız arasındaki mesafeyle orantılı olan üretim zamanına dayandığından, ilgili çözümler buna göre seçilmiştir. Sistemdeki kaynakların davranışı her çözüm için farklıydı. Bu nedenle, çözümlere OEE yüzdesi üzerindeki etkisine göre öncelik verilmiştir. OEE yüzdesi iyileştirmeleri kaynaklar arasında %1 ile %15 arasında değişmiştir. Her kaynak için en yüksek çözüm önceliğinin göz önüne alınmasının, maksimum sistem performansı ile sonuçlandığı görülmüştür.

Bu araştırmanın hedef sistemi, bir KOBİ'nin özelliklerini ve özelliklerini paylaştı ve sonuçlar, LSS ile birlikte ajan bazlı kontrol mimarisinin uygulanmasının performansı iyileştirdiğini belirtti. Her iki tekniğin de uygulanması, Endüstri 4.0'ın SME'lerin başarılı bir şekilde benimsenmesine doğru önemli bir adım atmakta ve zorlu pazara verdikleri tepkiyi geliştirmektedir.

Anahtar Kelimeler: Küçük ve Orta Ölçekli İşletmeler, Endüstri 4.0, Agent-based control, Lean Six Sigma, Time Study, Overall Equipment Effectiveness, Simülasyon İmalat Performansı ölçümü

To My Family

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AGV	Automated Guided Vehicle
C1	Coefficient of Idle Time
C2	Coefficient of Busy Time
FPS	Frame Per Second
FS	Functional Specification
IO	Input-Output
LMS	Lean Manufacturing System
LSS	Lean Six Sigma
MCDM	Multi Criteria Decision Making
MHESA	Material Handling Equipment Selection Advisor
MOST	Maynard operation sequence technique
MTM	Methods-Time Measurement
NVA	Non-Value Added
OEE	Overall Equipment Effectiveness
p1	Production Time
p2	Distance Between the Stations or Segments
p3	Speed of the Motion
SME	Small and Medium Sized Enterprises
SVA	Semi-Value Added
Tb	Busy time
Ti	Idle Time
VA	Value Added

Chapter 1

INTRODUCTION

1.1 Background

Nowadays, business with increasing globalization and rapid technological changes forced enterprises to move their production abroad by considering various features of customer satisfaction. This transformation requires more firms known as small and medium-sized enterprises (SMEs). In the entire world, SMEs are an important source of innovation, new products, and new services [1]. Therefore, the category of SMEs have become increasingly more important for the mentioned growth [2]. SME firms need to produce admirable products at low cost, short time delivery to market and appropriate quality. However, most SMEs are limited to knowledge and technology and characterized by tight resources [3]. The strategy to meet the demands at the high variety have made SMEs manufacturing systems more complex, dynamic and demanding [4]. On the other hand, the design of such manufacturing systems needs a suitable control architecture, high expertise, and careful decisions, in order to ensure that the system can successfully satisfy the demands of an ever-changing market [5]. Moreover, it is hard and highly risky for SMEs to implement these new control architectures and types of manufacturing system before validation and verification of their possible advantages and disadvantages and their effects on productivity [6]. Therefore, modeling, simulation and performance analysis play an important role in the successful development and implementation of a new manufacturing system and control architecture for SMEs [7].

1.2 Industry 4.0

"Industry 4.0" is the term which is used as the last industrial revolution. Industry 4.0 is headed by previous industrial revolutions in the history of the industry. In the 18th century, the first revolution began with mechanical production facilities. The division of human labor and electrification were the reason for the second industrial revolution which established in the 1870s. The third revolution which is known as "digital revolution" began due to the development of advanced information technology, automation, and electronics development in the 1970s [8, 9].

Industry 4.0 is expected to enhance the performance of enterprises by improving the manufacturing processes, resource and material utilization, and supply chain and life cycle management [10]. Industry 4.0 implementation in enterprises requires some principles to be followed and adopted. These principles are “Interconnection”, “Information Transparency”, “Technical Assistance”, and “Decentralized Decisions”. The main approach of Industry 4.0 implementation for SMEs is enabling intelligent communication between human and hardware resources [11]. Therefore, in SMEs, products, machines, material handling systems, human resources, and IT tools need to communicate intelligently with each other to organizing with the objective of improving overall production, not only within the physical boundaries of the company but also beyond them [12]. Decentralize control and decision is as a solution with facilitating modifications in the production process contributing to meet the increasing demands. Decentralized decision capability allows each definable section of the SMEs production system to act as an autonomous agent in completing their required tasks. Decisions will be separated throughout the system to maximize response time and optimize flexibility while continuing to operate [11]. This characteristic leads to having intelligent production including the knowledge of production history and products and actively steering products through the production process by instructing equipment to perform the required manufacturing tasks [13].

1.3 Material handling systems in intelligent production systems

Material handling system (MHS) is one of the most effective elements to deploy an intelligent manufacturing system. However, in order to implement intelligent production on enterprises in the context of Industry 4.0, there are some requirements for MHS which has to be considered [14, 15]. The process of handling the materials in most of the SMEs includes employees spending great time and effort to control the MHS by performing manual tasks, which resulted in higher production costs and longer production time [16]. However, the concept of the intelligent material handling has been developed which relies on Industry 4.0 implementation and it is all about utilizing new technologies to develop better control systems with better decisions [9, 17]. For most of the enterprises which are utilizing old fashion material handling systems, it would be risky and sometimes not feasible to apply any changes to transform to intelligent MHS. This transformation needs a new control architecture to make the system intelligent. Therefore, enterprises prefer to evaluate and validate any possible effect of the new control architecture for their current MHS [18].

1.4 Types of control systems

Adoption of Industry 4.0 in enterprises with getting benefits of the intelligent production system, require some modifications of the enterprise control system. The control systems should be distributed across the entire shop floor or resources unlike centralized control system that is common today [19]

1.4.1 Centralized control system

In a centralized control system, a central control unit controlling the operations of all the corresponding individual units. The central controller has the role of decision making, and all of the corresponding control units functioning depend on that. The individual controllers don’t have the ability to communicate, collaborate with each other [20].

1.4.2 Decentralized control System

The decision making in a decentralized system is not delegated to a central control unit. This type of control systems has a hierarchical structure which represents a combination of middle controllers (nodes) which control all external nodes and all of these nodes are communicating with a central control unit. In a decentralized control system, each controller will be controlled by the ones at the higher level and it can control the ones at the lower level. Thereby the whole system can be controlled by a central controller [21].

1.4.3 Distributed control System

A distributed control system is in contrast with centralized and decentralized systems. In this type of system, all of the controllers have equal power and decision making. Each of the controllers in this type of control system is known as an agent [22]. Each agent is able to communicate with other agents with following some protocols, principles, and architecture. The outstanding feature of this system is that if one of the agents fails to perform a task, the other agent can perform. Therefore, having more agents increases the reliability of the system [23, 24].

1.4.4 Control agents

In manufacturing control systems, agent systems have become an essential key technology. An agent is an active object which possesses certain capabilities to perform tasks, and it communicates with other agents based on the organizational structure to cooperate with the accomplishment of tasks [25]. Current manufacturing systems for SMEs are unable to deal with the evolution of products and market changes. Also, the SMEs need to maintain a satisfying performance outside normal operation. The Agent paradigm is supposed to overcome these difficulties with taking into consideration of essential concepts like automation and cooperation [26]. Agent technology, in this situation, becomes the right candidate to take on the new challenge and enhance the ability of implementation of Industry 4.0 [24].

1.4.5 Agent-based control system

This type of control system can be considered as a distributed control system which is a guide to a construct a software system with the aid of many existing agents [27]. Within Agent-based modeling (ABM) a framework is exhibited as a collection of independent decision-making agents. Each agent examines the system condition individually and makes certain decisions based on a set of rules and algorithms. Agents can perform different behaviors which are suitable for the correspondence system [28].

1.4.6 Master and slaves agents

In computer networking, devices can usually function in two specific modes; slave or master. The master which is considered as the principal device synchronizes communication throughout the network based on specific protocols and principles. Consequently, the rest of the devices are considered as slave devices. However, the slave devices are allowed to connect to master as well. The master has the ability to send data to any of its slaves and it can ask for feedback as well. Consequently, slaves are only allowed to send and receive data to each other with Master confirmation and commands [29].

1.5 Lean Six Sigma approach for performance evaluation and improvement of the manufacturing system

The implementation of Industry 4.0 has important and widely applicable effects or implications on enterprises. Investigation of these impacts and influences for enterprises are still scarce [30]. The most challenging impacts which need to be investigated are the ones coming up with utilizing new control architecture [31]. Although the new control architecture expected to be rewarding, it is also very challenging considering the possibility of any performance improvements for enterprises [32]. The expectations are very high that the new control architecture influences the performance of the manufacturing system positively. So that the rigors, risks and limitations which enterprises may face with, should be investigated after implementation of them.

Six Sigma is a set of approaches and methodologies including statistical tools and techniques to investigate, detect and eliminate the mentioned defects and limitations and increasing process efficiency [33]. Recently, Lean and Six Sigma (LSS) have become the most well-known technique for enterprises in deploying continuous improvement (CI) [33]. For every enterprise, especially SMEs, the most important aim is CI to have the best operational quality and improving their performance [34, 35]. Therefore, deploying LSS for SMEs improvs the relationship between manufacturing processes and variability and reducing defects. In addition, LSS mainly focusing on improving the processes with a close and accurate examination of causal relations through the collection and analysis of real data. The LSS process includes measurement, improvement and validation activities. Emerging methodologies and technologies which are the requirements of industry 4.0 implementation for enterprises, highlighted the need for LSS approach [36]. LSS uses the standard approach Define, Measure, analyses, Improve and Control (DMAIC) cycle [34, 36, 37]. (Figure 1.1)

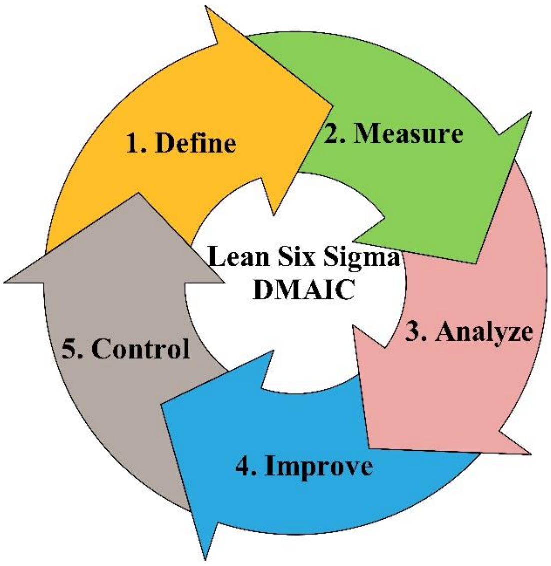


Figure 1.1: Lean Six Sigma

1.5.1 Lean Six Sigma “Define” phase

The first point that needs to be considered about the Six Sigma is the Define phase which is defining the Problem Statement. Refining the problem statement means narrowing down the scope of the problems and limitations to increase focus. In the “Define” phase of Six Sigma, the manufacturing system problems, limitations and defects along with the goals of the enterprises will be identified. The problem statement and goals have to be “Specific”, “Measurable”, “Achievable”, “Realistic” and “Time-bounded”[38].

1.5.2 Lean Six Sigma “Measure” phase

The second phase of Six Sigma is measuring the performance of the manufacturing system and related processes which will be considered as a factor to be improved. There several factors which are effective on the performance of a manufacturing system but the ones with higher influencing rate should be selected and measured. Data from the measured phase will be compared with data as the outcome of the system after modification to evaluate whether the improvement is effective or needs another improvement [35].

1.5.3 Lean Six Sigma “Analyze” phase

The third phase of Six Sigma is analyzing the measured data as the outcome of the second phase. This phase mainly identifies the main reasons for limitation, problems and defects in detailed. All of the processes in the manufacturing system including their tasks will be analyzed. This analysis is along with the data about the target factors to identify which one/s factor/s is the root cause for the defect [35, 39].

1.5.4 Lean Six Sigma “Improve” phase

In the “Improve” phase of Six Sigma, solutions and ideas to overcome or decrease the problems, limitations and defects will be identified. The desired value of the selected factors will be achieved by setting a range of process variables. The adjustment of the process variables can optimize the selected factor and improving the performance consequently [34, 39].

1.5.5 Lean Six Sigma “Control” phase

Control phase is the last phase of Six Sigma in which the main aim is sustaining the improvement made in the manufacturing system and its related processes. Various tools will be utilized to evaluate the variables which they are the most effective ones on the selected factors to improve the performance [39].

1.6 Overall equipment effectiveness (OEE)

Considering the “Analyze” phase of Six Sigma approaches for Industry 4.0, obtaining the effectiveness of the equipment plays a major role to have less number of defects and achieve higher productivity [37, 40, 41]. Overall Equipment Effectiveness (OEE) is an analytical performance evaluation method for enterprises, specifically SMEs [42]. The OEE is defined as the valuable time of operation over the loading time. The operation time can be interpreted as the time during which the equipment produces satisfactory products. Whereas the loading time is the needed time for equipment to run through a given period [43].

To evaluate the performance and productivity of enterprises, standard metrics play a major role. Performance improvement of the manufacturing system can be determined by utilizing these metrics [44]. Each metric can measure different sides of the production performance, such as efficiency, quality, flexibility, inventory, and profitability. Overall equipment effectiveness (OEE) is one of the metrics used to measure the percentage of the truly productive time. It is consisting of three factors which are availability, performance, and quality. Therefore, conducting OEE helps to correct and eliminate the wasted time and the bottlenecks that may occur in the manufacturing process [44].

In addition, OEE assessment of manufacturing system is not just limited to evaluating the manufacturing lead times. Investigation of OEE provides a systematic process to easily identify common sources of productivity losses [45]. OEE evaluation can also improve cost reduction, awareness, machine productivity, and increasing the life of the equipment.[46, 47]

There are three factors which have to be measured to evaluate the OEE. These factors are “Availability”, “Performance”, and “Quality”. The relationship between these factors and the evaluation of OEE is shown in equation (Equation 1) [48].

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality} \qquad \text{(Equation 1.1)}$$

Availability is the ratio of the run time to the planned production time and it takes the consideration of availability loss which are the stop times in the production process. Unplanned stops may occur because of equipment failure, lack of materials and planned stops might be caused by the changeovers. The remaining time from the whole production time deducted by the available losses is called the run time [44]. Availability can be achieved by the following equation (Equation 1.2):

$$\text{Availability} = \frac{\text{Run time}}{\text{Planned production time}} \qquad \text{(Equation 1.2)}$$

Here, if the availability is 100%, it can be concluded that there weren't any stop times during the whole production time [49, 50].

The second factor of the OEE is the performance. The performance takes anything into account that causes the production process to run at less than the maximum possible speed (including slow cycles and small stops) [51]. To calculate the performance the following equation (Equation 1.3) will be used:

$$\text{Performance} = \frac{(\text{ideal cycle time} \times \text{total count})}{\text{Run time}} \qquad \text{(Equation 1.3)}$$

Here, Ideal Cycle time is the maximum time to produce one unit of product. The total count is the total amount of products including the defects [48].

Quality is another essential factor in OEE calculation. This factor considering all of the products during the production process. It is also taking into account the quality losses that are the products with defects which cannot meet the defined quality standards and they need to be reworked to reach a certain level of quality. Quality factor using for OEE evaluation takes into consideration all of the parts that are manufactured whether they met the quality standards or not. The quality will be calculated by the following equation:

$$\text{Quality} = \frac{\text{good count}}{\text{total count}} \qquad \text{(Equation 1.4)}$$

Here, the good count is the number of the products that are manufactured and met the quality standards and the total count is the number of all of the manufactured parts. [52]. The overall method to calculate the OEE is illustrated as a flowchart (Figure 1.2).

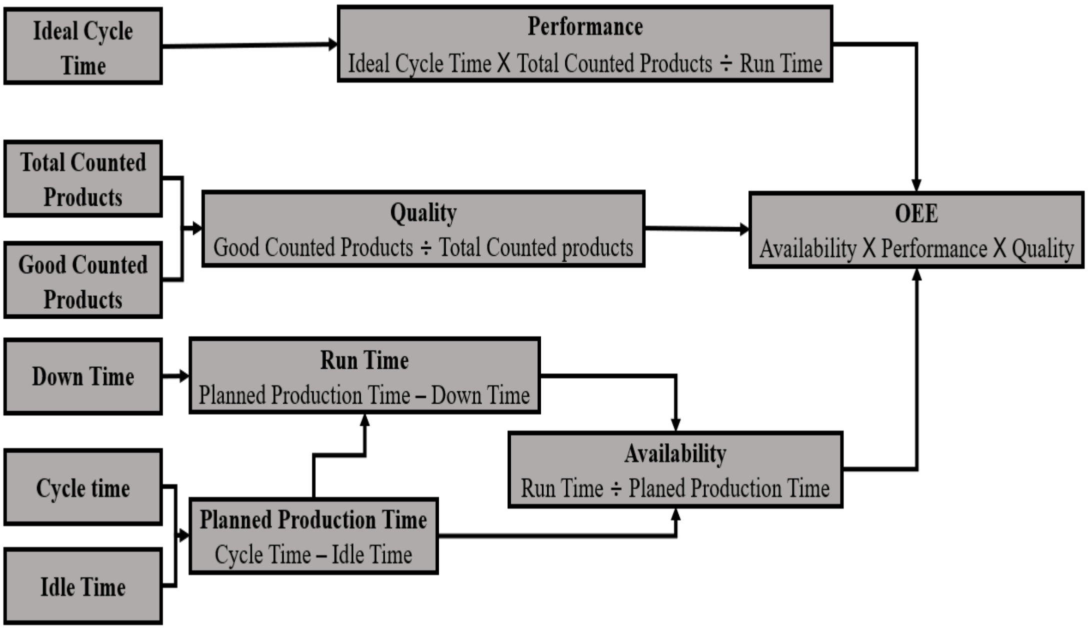


Figure 1.2: OEE overall procedure

1.7 Lead time and time study in OEE and LSS

Time plays the most essential role in analyses the OEE over the enterprises. In order to evaluate the system performance by utilizing the OEE standard, a comprehensive timing overview of the target system must be made [53]. A proper time study approach tracks the behavior of the entire production process and its related resource and tasks individually. Conducting the time study will help to identify and eliminate the wasted time and the bottlenecks that may occur during the process [54]. So that manufacturing lead time is one of the most effective factors for “Measure” phase of Six Sigma due to its importance in OEE evaluation and Time study techniques are playing an important role in "Analyze" phase of Six Sigma.

Time study data should be created in the standard format. There are several time study techniques for manufacturing performance evaluations. The most well-known techniques are Methods-Time Measurement (MTM) [55], Maynard operation sequence (MOST) [56] and Modular Arrangement of Predetermined Time (MODAPTS) [57]. To obtain an accurate time study result of the system, a combination of the mentioned techniques removes the lack of visibility across the organization to the time study data. Integration of the mentioned techniques with video studies can facilitate the procedure. Captured video of the manufacturing process can be imported into a time study tool. The video can be divided into segments associated with available recourses and tasks. It helps the time study results to be created rapidly and improves its traceability [58, 59].

1.8 The simulation for OEE and LSS

Simulation plays a significant role in evaluating, validating and verifying any optimizing idea and modifications for the manufacturing system's hardware, software, and layout design [60]. The operational performance of manufacturing systems could be obtained and validated after any changes in the simulation model before implementation on the real system [61]. Simulation refers to the behavioral reproduction of real-world processes or systems over time [62], while optimization seeks to find the best element from a given definition domain with regard to some criteria. In the last couple of years, simulation increasingly has been utilized as an efficient tool for optimizing the manufacturing systems [63, 64].

With considering the definition of simulation and its importance in the evaluation of the performance of the manufacturing systems, it can be concluded that simulation has a significant role in Six Sigma "Measure" phase. Therefore, for any possible solution to improve the performance of manufacturing systems, simulation can be utilized to measure the factors which are the most effective ones on the performance of the manufacturing system. However, identifying these factors and the way that they must be modified to improve the performance of manufacturing system require to be validated before implementation. The mentioned characteristic of simulation makes it one of the most effective tools in the "Improve" phase of Six Sigma.

In industry 4.0 implementation, there is a simultaneous emergence of decision-making distribution between control devices. The core objectives of the distributed decision making are understanding, analyzing, and optimizing operational conditions of systems [65]. Although the classical control architectures still are playing an important role in meeting operating goals, they have limited applicability to modern industrial systems. As Industry 4.0 is commonly referred to modern modern industrial system with higher degree of interconnectivity and feedback, the prospect of comprehensive understanding the influence of new control architecture for these system operations, became an important fact. Simulation is an effective tool to provides a general and powerful overview of industrial system performance before implementation of new control architectures [66].

ARENA is a discrete event simulation and automation industry-oriented general-purpose software, applied in a diversity of sectors (supply chain, manufacturing, healthcare, logistics, military, etc.) for addressing various business and industry challenges [67]. ARENA simulation could be utilized to reproduce different system configurations subject to optimization solutions, thus playing the role of validation, diagnostic and verification framework for solutions proposed by the optimization module [68-70].

1.9 The objective of the research

In the last decades, due to competitive global market demands, SMEs are imposing to improve their capabilities by integration into the Industry 4.0. Industry 4.0 concept for SMEs is achievable mainly by utilizing new collaborative, agile and responsive control architectures. A proper designed and implemented control architecture result in higher performance of SMEs which is key factor for manufacturing success in global market. However, SMEs must cope with many uncertainties related to implementation of new control architectures. The objective of this research is to develop a novel agent-based control architecture which is facilitating the Industry 4.0 adoption for SMEs by providing a distributed control. It is essential that the proposed control architecture come up with enough compelling reasons and solutions that will help SME’s deal with their uncertainties about modifying their current control system. The methodology identifies the problems and limitation and propose performance improvements. The methodology has a Lean Six Sigma approach including OEE as the performance measurement standard and an accurate time study technique to identify the defects and limitations of the system. Furthermore, a simulation tool has been utilized to deploy the optimization solutions to overcome the identified problems and defects before implementation on the real system. Implementation of the proposed novel agent-based control architecture and methodology in this thesis, lead to reach to improved performance of the manufacturing system and may ensure SMEs to take the first and most important step toward the implementation of industry 4.0.

The outline to achieve the objectives of this study is given as follows:

1. Selection of a system including the property of the SMEs as the target system
2. Investigation of the target system about the following:
    - System functionality and current scenario
    - Current control architecture and available control units and their tasks
    - Available resources and related task/s.
3. Developing a novel Agent-based control architecture with the following steps:
    - Categorizing the available control units to Master and Slave agents
    - Definition of tasks for each Slave agent (a slave for each Resource)
    - Definition of tasks for Master agent
    - Developing an agent software for Master and Slave agents including a precise decision-making ability

- Developing the communication protocols and principles between Master and slaves
- Developing the communication protocols between the slaves

4. Deploying Lean Six Sigma DMAIC to evaluate and improve the performance of the target manufacturing system including the developed agent-based control architecture.
5. Following the passes through five important phases of Six Sigma as follows:

- Define Phase:
    - ➢ Developing a problem and limitation statement of the target manufacturing system and its related processes
    - ➢ Identifying all of the available resources in the target manufacturing system
    - ➢ Identifying the production plan deployed in the target manufacturing system
- Measure Phase:
    - ➢ Developing a detail process map of the target manufacturing system
    - ➢ Developing a data collection plan
    - ➢ Collecting and measuring all of the required data
    - ➢ Validation of the collected data
- Analyse Phase:
    - ➢ Analysing the collected data from the last phase
    - ➢ Identifying the problems related to each resource, process or entire target manufacturing system
    - ➢ Identifying the Causal Factors for each of the detected problems
    - ➢ Identifying the root cause of the detected problems.
- Improve Phase:

    - ➢ Determining the possible and potential solution/s to overcome the detected problem in the last phase
    - ➢ Analysing the failure mode of the solutions
    - ➢ Identifying the target manufacturing system improvements
    - ➢ Validating of the improvements
- Control Phase
    - ➢ deploying a statistical process control to monitor the target manufacturing system after the implementation of the solutions and before them.

6. Running the target manufacturing system integrated with the developed agent-based control architecture to eliminate the basic problems ("Define" Phase of LSS)
7. Dividing the target system into different sections including the related resource/s ("Define" Phase of LSS)
8. Selection of a proper time study technique and a time study tool ("Measure" Phase of LSS)
9. Obtaining the time study results from each section during performing its task and preparing a comprehensive time study database ("Measure" Phase of LSS)
10. Validation of the collected time study result about the accuracy ("Measure" Phase of LSS)
11. Analysing the time study result to obtain the required information for performance evaluation of the target system and its related resources. ("Measure" Phase of LSS)
12. Selecting a proper performance evaluation technique which is Overall Equipment Effectiveness ("Analyse" Phase of LSS)
13. Utilizing the time study result in OEE to do the performance evaluation for each resource and the entire system ("Analyse" Phase of LSS)

14. Identifying the system problems and limitation by analysing the combination of time study and OEE results. (“Analyse” Phase of LSS)
15. Categorizing the identified problems into Hardware, Layout design and Control Architecture (“Analyse” Phase of LSS)
16. Identifying the most effective factors as the reason for the identified problems (“Analyse” Phase of LSS)
17. Suggesting the possible solution/s (optimization solutions) with considering the identified effective factors. (“Improve” Phase of LSS)
18. Generating the simulation model of the system including the proposed control architecture (“Improve” Phase of LSS)
19. Implementation of the suggested optimization solutions on the simulation model (“Improve” Phase of LSS)
20. Obtaining the system timing as the result of the simulation model after implementation of the optimization solutions (“Improve” Phase of LSS)
21. Obtaining the OEE percentage of the system after modification (“Improve” Phase of LSS)
22. Comparing the OEE percentages of the system before and after modification (“Control” Phase of LSS)
23. Identifying the resources which their performance increased after modification and the reason for these improvements. (“Control” Phase of LSS)

Chapter 2

LITERATURE REVIEW

2.1 Overview

This chapter provides an overview of previous researches about the implementation of the agent-based control architecture for SMEs with the view of facilitating Industry 4.0 adoption for this category of enterprises. Also, it introduces a roadmap to a successful evaluation and improvement of the enterprises by reviewing kinds of literature about the most proper techniques, standards, and approaches to comprises the objectives of the research described in the previous chapter.

2.2 Agent-based control architecture for the industry 4.0 implementation

Wan et al. (2016) presented a smart factory including several intelligent objects and products. Authors have stated that preparation of an enterprise integrated with smart objects and products leads to the implementation of a reconfigurable and flexible manufacturing system which are features of Industry 4.0. Authors in this study conducted a multi-agent system to be integrated with cloud technology and networking with smart shop-floor resources such as machines, conveyors, and products [71].

Prinz et al. (2016) conducted a methodology to interlink all resources related to manufacturing processes. Authors stated that the main target to Industry 4.0 implementation is the connection between the real physical resources. Authors also stated that in order to reach this goal new intelligent manufacturing control architectures should be utilized. Authors suggested multi-agent control as the target control system [72].

Santos et al. (2017) presented a strategic roadmap focus on key technologies required for Industry 4.0 adoption. Authors introduced eight subjects as cyber-physical systems (CPS), Internet of Things (IoT), embedded systems, Cloud Computing, services-oriented production, sensing, agent-based control systems, additive manufacturing and robotic [73].

Moeuf et al. (2018) conducted a literature review to analyses the production planning and control system of SMEs. Authors directed the literature review to be in the scope of Industry 4.0 concept. Authors highlighted the importance of the agent-based control system due to its influence on the flexibility of the manufacturing system. Authors stated that to facilitate the Industry 4.0 adoption, the flexibility of the manufacturing system plays an important role [74].

Bechtsis et al. (2017) provided a capability overview of material handling system in the Industry 4.0. The study focused on analyzing the effect of a new control system for material handling system which is the essential component of SMEs. Authors prepared a comprehensive investigation of the limitation of SMEs in the adoption of Industry 4.0. Authors suggested a proper control architecture and production planning as the most effective solutions [75].

2.3 Agent-based control architectures for manufacturing system (Material Handling Systems approach)

Chan et al. (2011) proposed a model for improving material handling system called material handling equipment selection advisor (MHESA) [76]. Lewandowski et al. (2013) pointed out the benefit of multi-agent communication among the physical interfaces. The authors conducted a methodology to evaluate the benefits of a Multi-agent communication by implementation on material handling system among an enterprise [77]. The authors stated that they faced certain problems during the implementation of a new control architecture on a selected material handling system. The main issues that authors mentioned are external interfaces, legacy system integration, conflict resolution, overall system control, system dynamics, communication, system architecture, ontology management, and control architecture. They stated that the majority of the mentioned issues can be relevant by utilizing a type of manufacturing control system which has the properties of an agent-based control architecture [76, 77].

Johnstone et al. (2010), applied the concept behind agent-based control. This concept plays a huge role in preventing the material collision in a material handling system. The authors realized that an effective layout of material handling lines was significantly required for the parts to follow the right path without facing any obstacles. Moreover, to obtain the desired differentiation in the merging point on the target MHS, the gaps between the objects were maintained. Authors concluded, this can be only achieved by an agent-based control architecture to feed conveyor and input/output lines management, intelligently [78].

Lau and Woo (2008) developed an operator designed routing methodology for material handling system [79]. They proposed a material handling system including agents associated by single direction connections control purposes behind the arrangement of MHS and named it as collaborating node. To settle on directing choices, they characterized the most suitable route in terms of degree of tolerance to unexpected factors and material workload balancing. The authors position this approach as distributed real-time-state and map a general characterization of directing procedures [79].

2.4 Importance of manufacturing system performance evaluation

Jain et al. (2011) stated that a higher manufacturing performance leads to better competitiveness ability for enterprises. Authors defined two stages for having a successful enterprise in a competitive market. The first stage is identifying the competitive priorities and the second stage is determining the critical manufacturing aspects which leads to superior manufacturing performance [80].

Wakjira and Singh (2012) stated that a proper measurement system for evaluating the performance of the enterprises helps the management to take a comprehensive control of the enterprise and production improvements consequently [81].

Hon (2005) stated that manufacturing system performance evaluation is the most essential subject for improving the objectives of an enterprise. The author stated that the direct relationship between the enterprise control system and the performance of the manufacturing system. The author also stated the possibility of an extremely accurate physical or mechanistic performance measurements, but he mentioned that the enterprise performance evaluation maybe unsettled subject due to the multi-dimensional and diverse nature of manufacturing system [82].

Abdi and Labib (2011) investigated the efficiency of several conventional methods for manufacturing systems performance evaluations. Authors stated that it is essential to consider several manufacturing aspects which are distinguished in conventional evaluation methods. Authors highlighted the importance of the manufacturing systems performance evaluations by investigation of its influence on decreasing the enterprise's uncertainties caused by many external factors [83].

Bol et al. (2016) carried out research about the relationship between the design of the control system and managers' rating decisions and behavior. Based on authors findings, control system design elements effect on the accuracy of the required information to evaluate the transparency of performance evaluation [84].

2.5 Lean Six Sigma approach for manufacturing system performance evaluation and improvement

Ramesh et al. (2016) illustrated the utilization of Lean Six Sigma to improve Overall Equipment Effectiveness (OEE) in the small and medium-sized enterprises. Authors in this research stated that SMEs should increase and improve their performance efficiency and quality continuously. In addition, the authors mentioned that a low percentage of OEE led to high costs due to products re-inspections and reworks. Therefore, the authors suggested that six sigma implementations will identifies and removes the problems and improves the manufacturing system performance which will increase the OEE [37].

Albliwiet et al. (2015) conducted research to deploy continues performance improvement for manufacturing enterprises. Authors stated that Lean Six Sigma has the most effective strategies in order to have a continues improvement for the performance of manufacturing systems. Authors concluded that Lean Six Sigma approaches help enterprises to achieve operational and quality excellence and enhance performance consequently [36].

Swarnakar and Vinodh (2016) conducted a process improvement with the business view and Lean Six Sigma strategy for enhancing the performance of manufacturing enterprises. Authors stated that the utilization of Lean and Six Sigma- DMAIC strategies will decrease the defects and eliminate non-value-adding tasks in the manufacturing system. Also, the authors stated that Lean Six Sigma framework improvs the key metrics in the target manufacturing system [85].

Habidin et al. (2016) conducted a methodology to determine the relationship between lean Six Sigma implementation, Manufacturing control system and manufacturing performance measurement. The author conducted a mediator model which shows the relationship between the presence of a proper manufacturing control system and Lean Six Sigma and Performance of manufacturing system. Authors stated that the analysis result through the proposed method showed that a proper manufacturing control system will improve the performance of manufacturing system when coupled with Lean Six Sigma [86].

2.6 Time study techniques for Lean Six Sigma and manufacturing system performance evaluation and improvements.

Franchetti, (2015) stated that in order to analyze a manufacturing system, determining the production rate or system capacities and related cyclical patterns are required. Authors introduced time study as an essential requirement to collect data for analyzing the mentioned subjects to analyze a manufacturing system. The author also stated that a time study shows the behavior of the manufacturing system to accomplish some specific tasks. The author concluded that the data and the information as the outcome of an accurate time study flow into a successful Lean Six Sigma evaluation. Author illustrated the time study as the key factor for “Analyze” and “Measure” phases of Lean Six Sigma by conducting a comprehensive case study [87].

Lande et al. (2016) investigated the critical success factors of Lean Six Sigma framework for small and medium enterprises. The author stated that identifying these critical success factors leading to a proper Lean Six Sigma framework which affect the quality and performance of small and medium enterprises. Authors intended to illustrate the importance of selecting appropriate time study tool to identify the most effective critical success factors to obtain the effective implementation of Lean Six Sigma [88].

2.6.1 Classic time study techniques

In the study by Al-Saleh (2011), study process charts, flow charts, activity chart time tables used to detect the work processes of handling, operation, storage and delays [89]. Gruzauska et al. (2016) investigated the flow charts used also to indicate the transportation, preparation and shifts times [90].

Gilad (2006), conducted a time study in a textile factory to obtain standard time for a printing-machine to calculate the performance rating by utilizing the speed-rating-technique. The author utilized a methodology included a classical observation for three operations by dividing them into small elements. The author concluded that the most time-consuming operations are the ones requiring the constant attention of operators. The author also mentioned that in time study observation, variables were not controlled, and the study only investigated the machine and related operations, human labors and their performance. Therefore, the author concluded that the study cannot be used for comparison with the other system with different variables [91].

Gružauskas et al. (2016) conducted a study which aimed to utilize the labor and machine productivity and flow process chart to analyze the production process. Authors stated that there are lots of idle time due to some long process unparallel with other activities. So that they have suggested that some independent activities should be done at the same time and parallel to each other [90].

Bon and Daim (2010) investigated the time as a measurement tool for the performance evaluation of an enterprise. Time measurement was used to arrange tasks available in the enterprise. The aim of this study was increasing the production and decreasing its cost that contained a lot of time-consuming operations [92].

2.6.2 Method time measurement as a predetermined time study technique

Longo and Mirabella (2009) conducted a different tool to design an assembly production line. Since the study was based on a nonexistence assembly line, a simulation tool has been used. For simulation of the workplace with a qualified worker another simulation tool integrated with Method Time Measurement (MTM) as a time study technique has been utilized to analyze the primary model of the assembly line.

The results show bottlenecks in some stations, inappropriate distribution of tasks in some stations and other problems regarding the ergonomics of the labors and working condition. Some modifications were applied which reveal as the best work method, line balancing and eliminating ergonomics risks [93].

Kuhlang et al. (2011) presented a study on an assembly line and production-logistic process which aims to create more added value elements in process within a fixed time. Authors aiming a faster process with more time available to produce rather than more production in the fixed / same duration. To achieve this goal, a combined methodology including MTM as a hybrid optimization of added value is used. Due to the detailed analysis characteristic feature of the methodology, the results showed high identification and elimination of waste time. Thus, lead to design a more efficient process with lower lead time and higher productivity [94].

De Almeida and Ferreira (2009) conducted mythology by utilizing MTM which was implemented on two automotive company and household appliance manufacturing company. MTM used mainly for developing time table data that helps in planning, organizing the work process and for utilization of the available resources. Authors stated that MTM is a significant tool to identify the unnoticed small-time wastes. They also mentioned that MTM is not a competitive neither alternative with other time study tools but a complementary tool where it only produces timetables [95].

2.6.3 Maynard operation sequence technique time study

Karim et al. (2016) investigated the effectiveness of applying Maynard Operation Sequence Technique (MOST) time study technique in an automated enterprise. To make improvements in the system, video of the available stations was captured, and tasks were examined by MOST. By applying MOST and standardizing the time for each task and whole the system, the cycle time reduced significantly [96].

Gupta & Chandrawat (2012) investigated the performance of an SME in Japan, used for mass production which helps firms to produce more products with lower resources. Authors stated that MOST are the more practical method that can identify the non-added value work by measuring the work and can be applied to any type of task [97].

2.7 Overall Equipment Effectiveness for Lean Six Sigma and manufacturing system performance evaluation and improvements

Gibbons (2006) conducted a methodology including Overall Equipment Effectiveness (OEE) as an indicator of enterprise effectiveness to be concurrence with the Lean Six Sigma-DMAIC improvement methodology. The Author illustrated the benefit of OEE in providing data related to enterprise potentials. The Author state that for the Lean Six Sigma process can possibly eliminate the need for failure mode and effects analysis. The author concluded that OEE can be utilized to analyze the captured data of the system which is required for effect analyze of the system and obtaining the potential of the system [98].

Gibbons (2010) introduced a framework for measuring Six Sigma process capability using the data from the OEE. The author stated that enhancing OEE combines asset management effectiveness, net process performance, gross process performance, measures of process effectiveness and Six Sigma process capability into a single lean Six Sigma key performance indicator of enterprise performance [98].

Mandahawi et al. (2012) presented a study to improve the performance of manufacturing enterprises including Lean Six Sigma strategies. Authors utilized Lean Six Sigma-DMAIC methodology and several lean tools to improve the productivity of the target manufacturing system. Two performance measures namely The Overall Equipment Effectiveness and production rate were utilized to evaluate the performance of the manufacturing system before and after the Lean Six Sigma- DMAIC cycle [99].

2.8 Overall Equipment Effectiveness and time study relationship

Ghafoorpoor Yazdi et al. (2018) conducted a methodology in which result of a comprehensive time study of a material handling system was utilized as the key factor for evaluating the Overall Equipment Effectiveness (OEE) of the system. The author stated, the OEE tool is designed to identify losses that reduce equipment effectiveness. Author concluded that these losses are tasks that absorb resources but create no value [100]. The authors stated that there are six major losses available in manufacturing system which are the distance between the resources as layout design limitation, downtime, speed, idling and minor stoppage and Reduced speed losses [100].

Puvanasvaran et al. (2013) conducted a study aims to improve the overall equipment effectiveness of autoclaves machines in the aerospace industry using a time study method. The study performed in two steps. The first step is using a stopwatch time study to calculate the current OEE percentage. The second step is using Maynard's Operation Sequencing Technique (MOST) to enhance the OEE percentage. Authors stated that the MOST is significant to indicate the added value activities and non-value-added activities through each step of the process [101].

Patel (2015) performed a stopwatch classic time study. Authors stated that stopwatch is always the best way to study manual work because human performance is not always the same. The author obtained the cycle time for manpower works and with the help of overall equipment effectiveness (OEE) standard, minimize the cycle time of overall shift. After performing time study, standard times established and by proper actions cycle time was reduced in operations and numbers of human labor were reduced [102].

2.9 Computer-based simulation for Lean Six Sigma and manufacturing system performance evaluation and improvements

Yang et al. (2003) provided a clear and comprehensive coverage of all the important, organizational, implementation, technical and philosophical aspects of designing a proper Six Sigma. Authors introduced computer-based modeling and simulation as an effective concept to design proper Six Sigma strategies. Authors stated that a computer-based simulation helps to ensure the efficiency of new optimization concepts which are subjected to the “improve” phase of Six Sigma. Authors also stated utilizing computer-based simulation helps to ensure new process optimization concepts are going to come up with the right functional requirements [103].

Naeem et al. (2016) conducted a simulation model to define the storage area needed for the fabric manufacturing industry. The author in this research utilized a simulation software to build a model that represents a real system with all the physical components and available tasks. The authors implemented their methodology on the simulation model to enhance the real system performance [104].

Jayant et al. (2012) developed a simulation model using Arena software to evaluate the future performance of the system. In this study, the authors obtained resource utilization, cycle time, transfer cost, and transfer time [105]. Zahraee et al. (2014) conducted a study to investigate company productivity development by using Arena simulation software. In this study, optimum factors that have a major impact on the production of the company was obtained by analyzing the obtained results from Arena simulation [106].

Maropoulos and Ceglarek (2010) represented the concept of verification and validation in the product lifecycle. Authors conducted the validation and verification techniques by analyzing the graphical behavior of the simulation model and compare it to the real system. Authors stated that the study was extended for every single part of the model by analyzing the output data and it was led to effective and efficient results [107]. Sargent (2013) briefly summarized the verification and validation process in a study with supported techniques. Moreover, the author proposed using the graphical behavior of the simulation model as a useful technique for validation [108]. Macal (2016) conducted a well-defined explanation of the validation and verification of agent-based subject through the simulation model and analyzing the simplest realistic rules of its behavior [109].

2.10 Literature review conclusion

The first objective of this chapter was to review the roadmap in Industry 4.0 adoption for Small and Medium-sized enterprises and obtain the principles of implementing Industry 4.0. Several studies which investigated the principles of Industry 4.0 within the last decade were reviewed. The studies stated that a new collaborative, agile, and responsive control architecture are required for SMEs to facilitate the industry 4.0 adoption.

Therefore, the literature review was narrowed to agent-based control architectures applicable to SMEs and Master-Slave was selected as the most appropriate agent-based control architecture. Likewise, illustrated the limitations, problems and uncertainties of SMEs in modifying their currents control architecture. Different researchers have attempted to define Lean Six Sigma-DMAIC strategies to evaluate and improve the performance of SMEs. Thus, Lean Six Sigma has been chosen and best techniques for associated phases reviewed (Define, Measure, Analyze, Improve and Control).

It was concluded that a suitable data collection technique is needed to provide the required system data for “Measure” phase of the Lean Six Sigma. Therefore, a proper combined time study technique was selected. Furthermore, Overall Equipment Effectiveness (OEE) was chosen for “Analyze” and “Improve” phases of the Lean Six Sigma. “Measure” and “Analyze” phases of Lean Six Sigma help identifying the problems, limitations and possible solutions to improve the system performance after implementing the proposed control architecture. All these possible solutions should be investigated to overcome the identified problems and limitations of the system. Based on the literature, discrete event simulation is the proper tool for this purpose. Therefore, the real system was simulated to implement these solutions and modifications. The result of this simulation was utilized for “Measure” and “Improve” phases of Lean Six Sigma.

Reviewing to date literature about each research objectives, revealed that there is a gap to adopt the SMEs requirements and Industry 4.0 principles. This gap is due to the SMEs characteristics and uncertainties to modify their currents manufacturing system. The proposed novel agent-based control architecture, and the methodology to evaluate and improve the performance of SMEs, facilitate the adoption of the Industry 4.0 to fill the mentioned gap after utilizing this control architecture.

Chapter 3

METHODOLOGY

3.1 Overview

This Chapter adopted a case study approach methodology to illustrate the design and implementation procedure of a novel agent-based control architecture for SMEs. The study sought to create a novel roadmap for performances evaluation and improvement strategies and techniques for the target system after the implementation of the proposed novel control architecture. Evaluation and improvement approaches are combined with the use of Lean Six Sigma strategies. Time study, Overall Equipment Effectiveness (OEE) and discrete event simulation are utilized to provide the required system data and information for different phases of Lean Six Sigma.

3.2 Design of the agent-based control architecture with Maser-Slave mechanism

The agent has different computing paradigms and each of these paradigms has several roots as far as theory and required technologies. These paradigms and their requirements can be categorized into two main abstractions which are as follows:

- An agent is a computational system with autonomous and intelligent behavior capabilities.
- An agent has the interacting capability with other agents

In this thesis, in order to follow the mentioned abstractions for an agent in the proposed novel control architecture, an agent-based control architecture with Master-Slave mechanism was selected as the target.

3.2.1 Structural definition of the proposed control system

In the design of the proposed agent-based control architecture, agents task division, allocation, and communication patterns were the main concerns. Master-Slave mechanism was required to delegate the tasks in salve agents. The proposed agent-based control architecture with Master-Slave mechanism included three individual layers which were Physical Resource layer, Physical resources control layer, and management layer. For each layer, based on the characteristic of an agent-based control architecture with Master-Slave mechanism, required features were defined. In addition, the communication and interaction protocols between each layer were defined with considering the required network and its associated interfaces.

3.2.1.1 Physical resource layer of the proposed control architecture

This layer in this thesis includes the category of physical resources which covers all the operational resources concerned with the physical capabilities to deliver the required tasks. As the main operational task for the target system is handling the material based on the planned scenario, most of the resources are material handling equipment such as Robot, Conveyor and Sliding units. Besides the material handling resources, another category of physical resources was required to cover the detection and measurement tasks. Different type of sensors was utilized to detect the material existence in some specific spots on the material handling systems. In addition to distinguish the material on a material handling system, some sensors were utilized to measure the required physical variable to detect the object’s color (Figure 3.1).

3.2.1.2 Resource control layer of the proposed control architecture

This layer of the proposed control architecture has two levels or layers of control, as shown in Figure 3.1. At the lower layer, there is a set of control units as Slave agents which have the control task of the resources associated with the physical resource layer; and the top layer Master agents control unit is functioning which has the coordination task for slave's interactions and communications.

3.2.1.2.1 Slave agents in the resource control layer

Controlling the associated resource/s among the target system was the main task of Slave agents. These agents are capable of doing several tasks which have to be defined, created and transferred to them before utilized in the system. The control architecture was designed to invoke the task based on the system requirement to execute an order and some sort of communication and cooperation protocols for collaboration with other slaves. Therefore, a slave agent included the following:

- **Software agent:** In this thesis software agent is an intelligent control software includes the program for controlling the related resource/s and a program to manage the interaction with other slaves and master agent in a cooperative manner. This interaction is sometimes in a competitive manner between the other slaves.
- **Interaction protocols:** In this thesis each salve agent attends different protocol/s to interact appropriately with other slaves and the master agent. For instance, responding to message from other slave agents, performing actions in their respective tasks, or transferring their local states to other slaves and master. Thus, these protocols were considered as a way to specify the policy that slave agents should follow in interaction with each other and with the master agent.

- **Agent communication language (ACL):** The communication between Slave agents and the Master agent was key to realizing the potential of the agent-based paradigm in the proposed control architecture. Slave agents required an Agent Communication Language for communication to exchange information and knowledge to other slave agents and the master agent. In this thesis, Foundation for Intelligent Physical Agents (FIPA) was utilized as the Agent Communication Language.

3.2.1.2.2 Master agents in the resource control layer

The master agent acting as the dispatch of all slave agents provides collaborative communication among the slave agents and determines the optimal configuration of the related task/s for each slave. Therefore, the master agent included the following:

- **Cooperation mechanism between slave agents:** Protocols for sending and receiving messages as well as functions for wrapping various type of data, which was required to perform tasks belongs to each slave agent. In addition, the master agent includes the required communication protocols and performs authentication, authorization, access control, and privacy functions.
- **Resource planning:** The master agent requests the order from the management layer. Each order for each product activates a process of dynamic design of the system to accomplish that order. This process includes the respective resources and associated tasks. The master agent is responsible for the selection of the resources needed for the required processes. The target system in this thesis is designed for part differentiation based on a predefined physical attribute of parts (color). There are four defined processes to accomplish part differentiation and each process included a different set of resources with associated tasks.

3.2.1.3 Management layer of the proposed control architecture

In this thesis management layer is receiving the other which is the quantity of the parts with a specific attribute (color) and associated buffers which are the exit points in the system to unload these parts after differentiation. In this layer, the order will be analyzed, and the required processes will be defined to accomplish the order. By considering all of the required processes for executing the order, the process plan will be generated which will be transferred to the master agent.

3.2.1.4 Communication between control architecture layers

In the proposed control architecture, there are specific networks and connection protocols to support communication among the physical resources, agents, and management layers. A peer to peer connection was considered to provide the communication requirement between slave agents and physical resource layer which are material handling devices and measurement or detection equipment. In order to enable the communication between slave agents in the physical resource layer, and also providing the communication protocols for them by the master agent, a Personal Area Network (PAN) was created. In this thesis Slaves and master are communicating via this PAN over Bluetooth connection (figure 3.4).

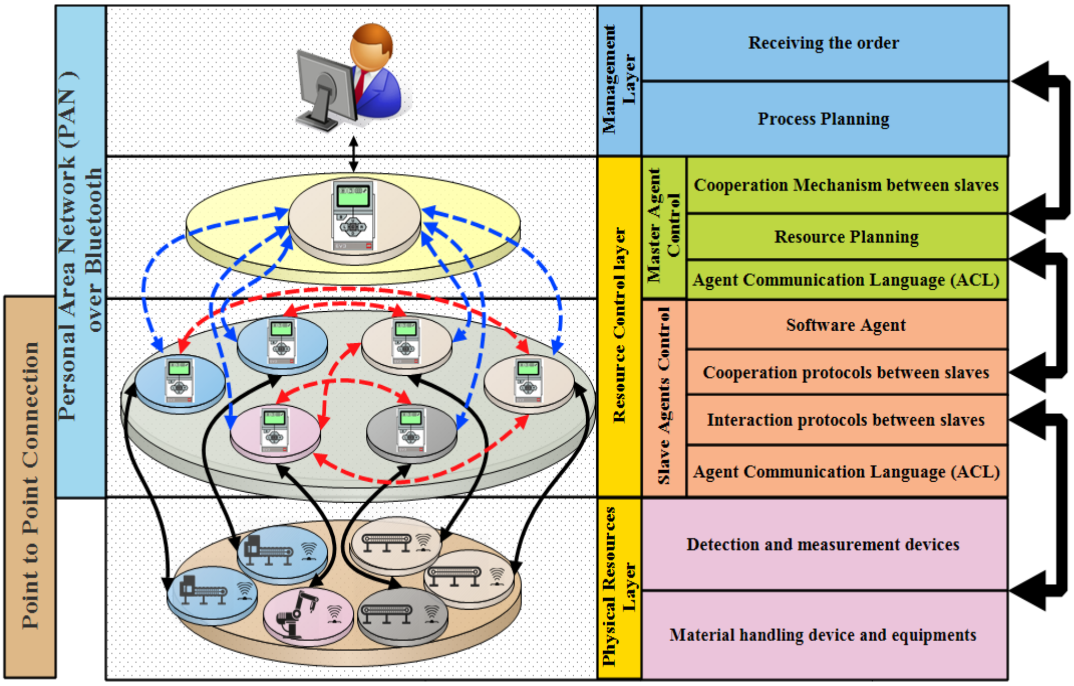


Figure 3.1: Proposed Agent-based control architecture with Master-Slave mechanism

3.3 Case study system description with the agent-based control architecture

In order to implement the proposed agent-based control architecture with a master-slave mechanism, a manufacturing system was required which has the character and features of the SMEs. Therefore, a simple manufacturing system for educational purpose located in the German University of Technology in Oman was selected. The system was composed of different types of Material Handling System such as conveyors, robot arm and sliding units. The target system had few numbers of discrete controllers without any specific communication ability. Handling the loaded material based on a predefined sequence by the operator to the system was the only task for the system.

3.4 System description with the agent-based control architecture

In order to implement the proposed agent-based control architecture on the target material handling system, it was necessary to do some minor hardware modification such as integrating the system with more sensors. In addition, a comprehensive task definition including the required resources to accomplish the target tasks was needed. Figure 3.3 illustrates the system layout design after the integration of the required sensors. The system consists of a main conveyor including 4 sensors, a robot arm, two side conveyors (left and right) including a motion sensor and two sliders (left and right) including a color sensor. Conveyors were powered by two sets of servo motors (Four Motors) and sliders were powered by one motor on each. Conveyors, sliders, and robot were controlled by individual slave agent. The slaves were receiving signals from sensors as input to provide output signals to the resources. The master and slave agents are illustrated in Figure 3.2.

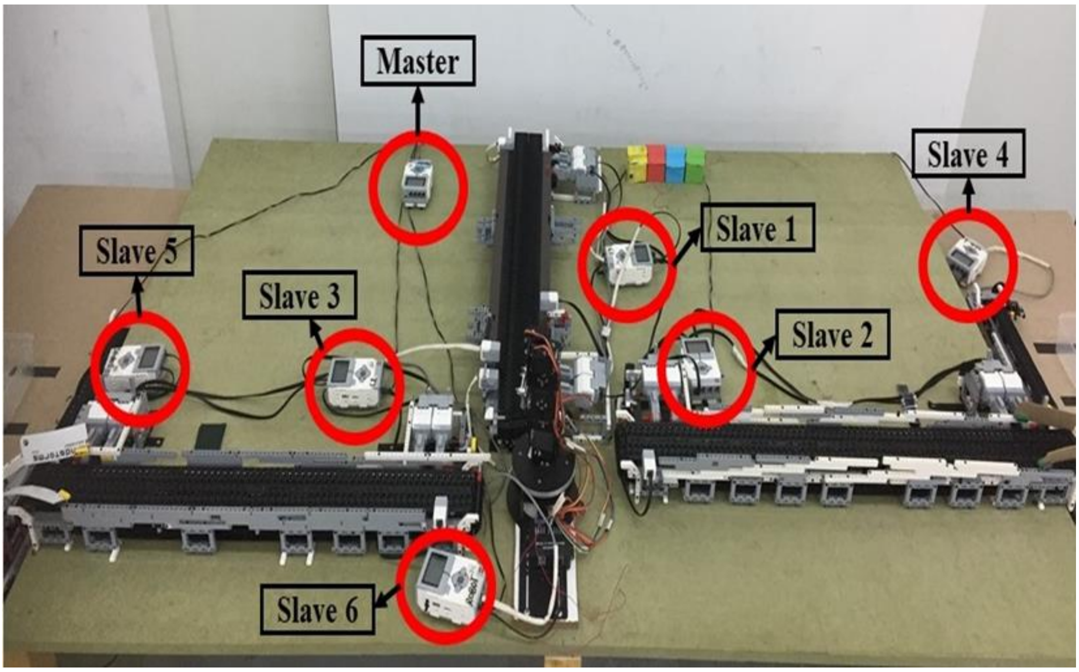


Figure 3.2: System overview

In order to accomplish the communication, cooperation and transferring information among slaves and master agent effectively, all of the agents were communicating concurrently with a shared perception network (figure 3.4). There was a need for a coordination protocol that will guide and support the interaction of slave agents to each other and master agent which were defined as the Master agent task in the system.

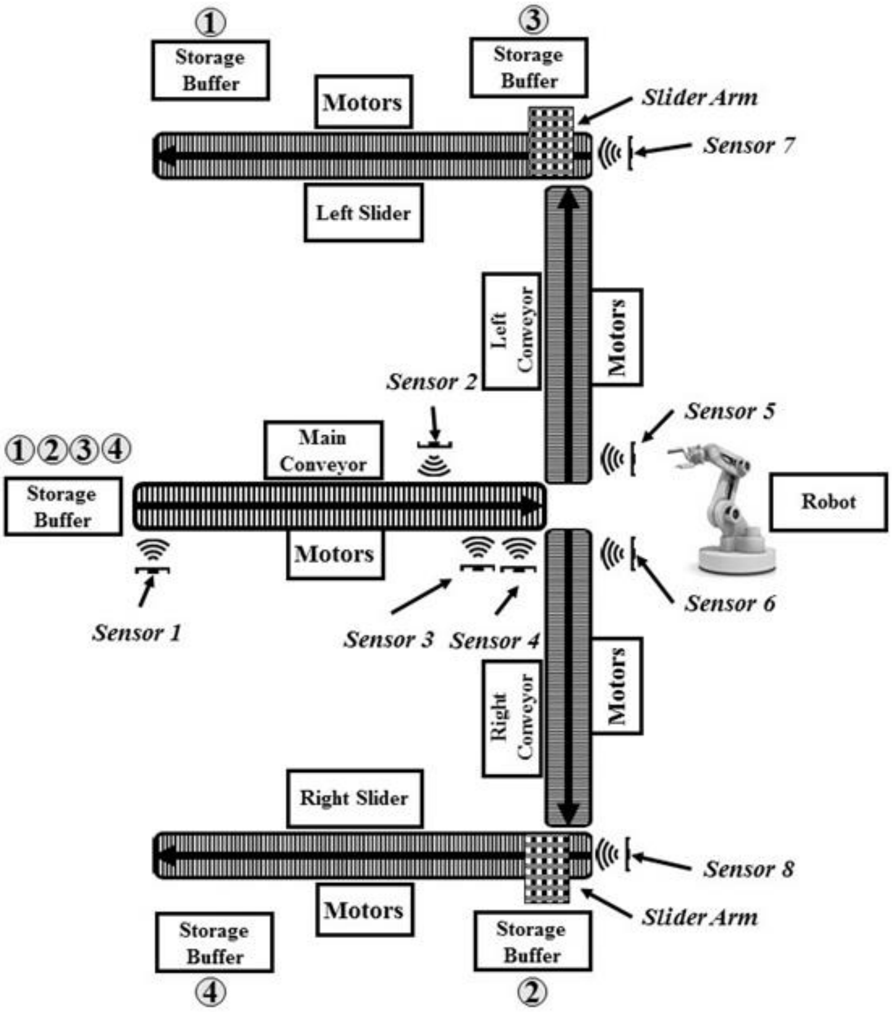


Figure 3.3: Layout design –Top view

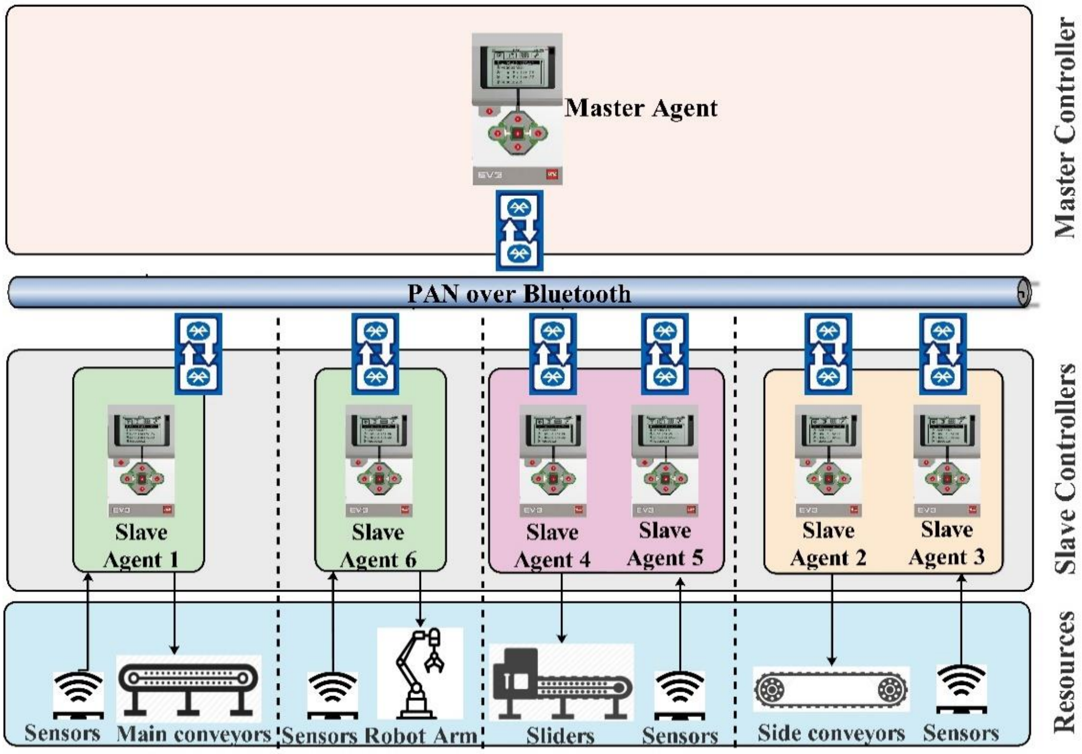


Figure 3.4: Communication in the proposed agent-based control architecture

Referring to figure 3.3, the system can be divided into 4 main district or sections. The first section comprises of 4 sensors, storage for materials (Red, Blue, Yellow, and Green), main conveyor and slave agent1. Section 2 consists of the robot arm and slave agent 6. Section 3 and section 4 are similar, except that they are in the opposite direction and assigned for handling different objects. Both sections 3 and 4 consist of two slider unit integrated with a color sensor and controlled by slaves (Slave agent 4 for the right side and Slave agent 5 for left side), two conveyors integrated with a motion sensor and controlled by slaves (slave agent 2 for the right and Slave agent 3 for left side) and unloading buffers. The unloading buffers are the outlets/exits of the target system in which materials are going to be unloaded separately in each of them based on their color and the planned scenario.

Each section in the target system has different functionality and individual control architecture. In the first section, sensor 1 (Infrared sensor) was utilized to initiate the main conveyor. Sensor 2 (Infrared sensor) was added to the system to slow down the conveyor motion to place the objects in a specific position accurately. Slowing down the conveyor made sensor 3 able to have enough time to detect the presence of the object and increase the accuracy of the system. The robot arm was programmed to pick the material from a specific position on the main conveyor and place it on the left or right-side conveyors (Figure 3.5). Hence it was necessary to slow down the main conveyor motion to increase the accuracy of sensor 2 and eventually sensor 3 to be able to stop the conveyor and object in the exact desired position (Figure 3.3).

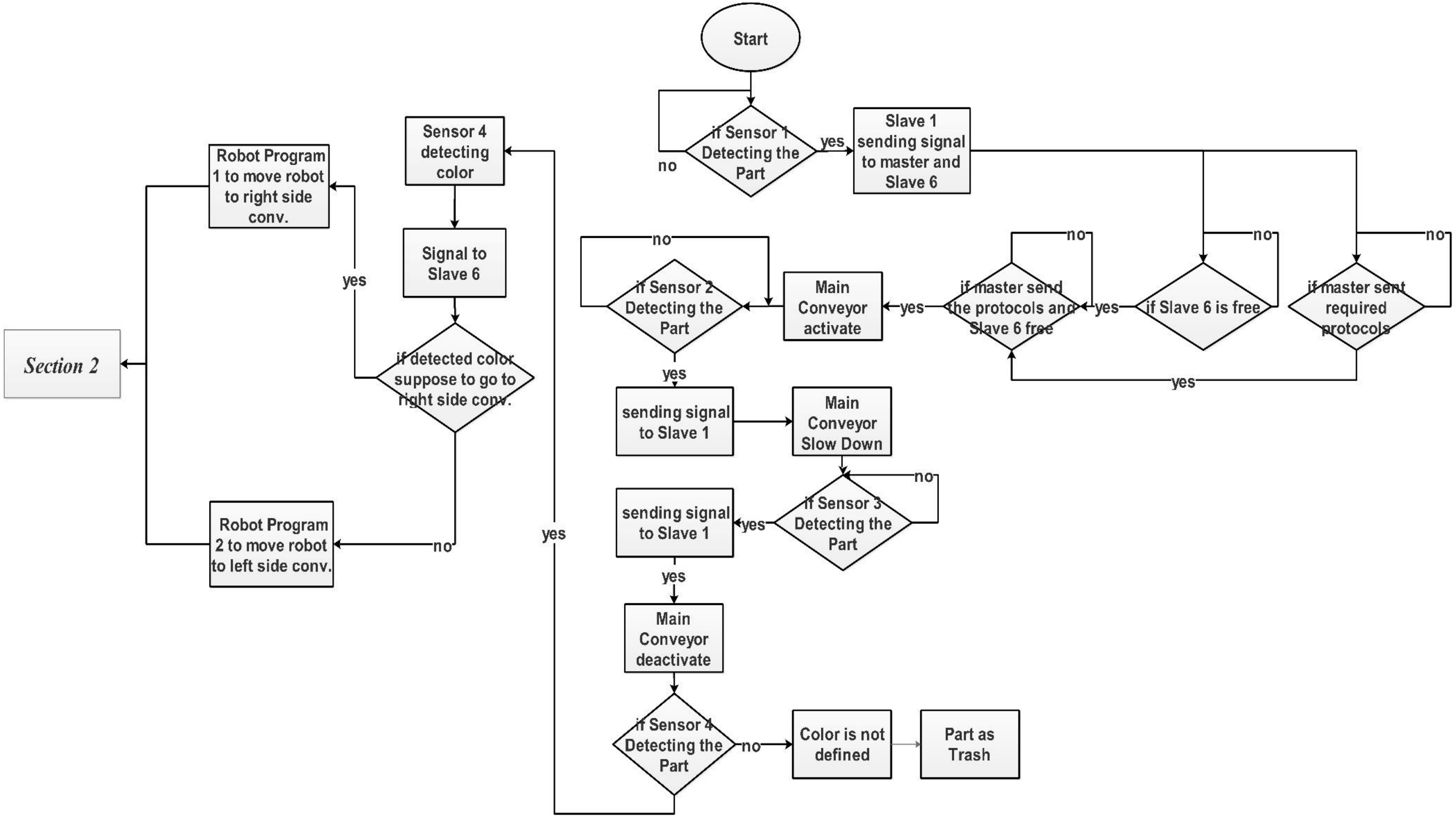


Figure 3.5: Main conveyor and robot arm control algorithm (section 1)

The main resource for the second section is a robot arm. The robot arm’s task was to pick the object from the main conveyor and place it either on the right or left conveyor depending on its colors and the considered plan for that color (Figure 3.6).

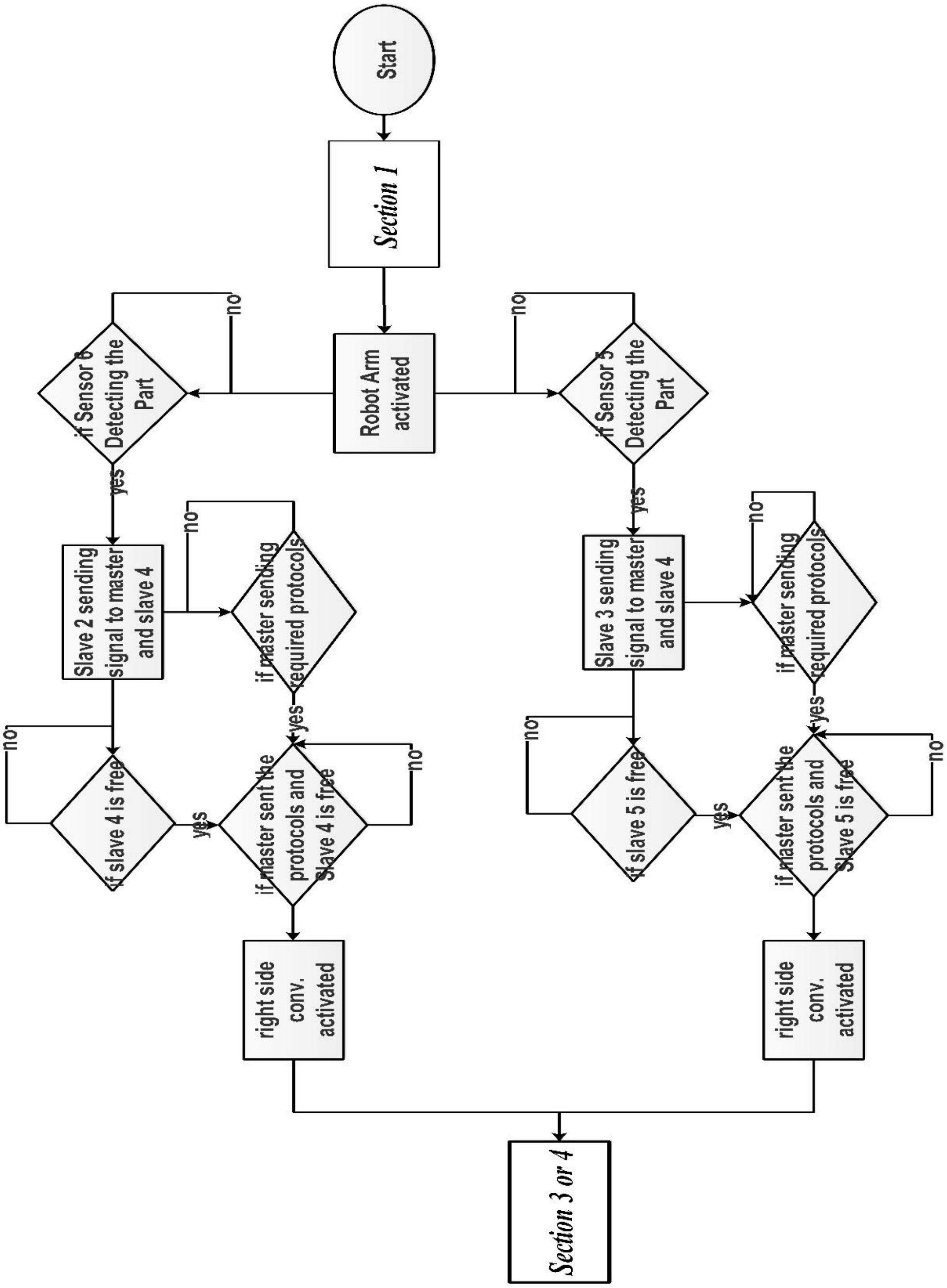


Figure 3.6: Robotic arm and side conveyors Control algorithm (section 2)

As the aim of the proposed agent-based control architecture was distributed control arability for each resource, two individual controllers were assigned for main conveyor and robot arm respectively. Furthermore, in order to enhance the intelligence agent software, for each slave agent, the system was integrated with more sensors. With considering the most important feature of agent-based control architecture, a communication algorithm was developed between slave agent 1, slave agent 6 and master agent to enhance the interaction between main conveyor, and robot respectively. To implement the mention communication algorithm among the section 1 and section 2 (Main conveyor and robot arm), the required communication and interaction protocols were defined on Master agent and associated slave agents (Figure 3.8).

In section 3 and section 4, two sensors were added at the beginning of each left and right conveyors. These sensors were utilized to initiate the side conveyors (Figure 3.3). Since the object should slip to the slider for differentiation based on their color; once the object slips to the slider, the sensor on the slider was distinguished the color of the detected object and distributed the object to the target buffer accordingly (Figure 3.7).

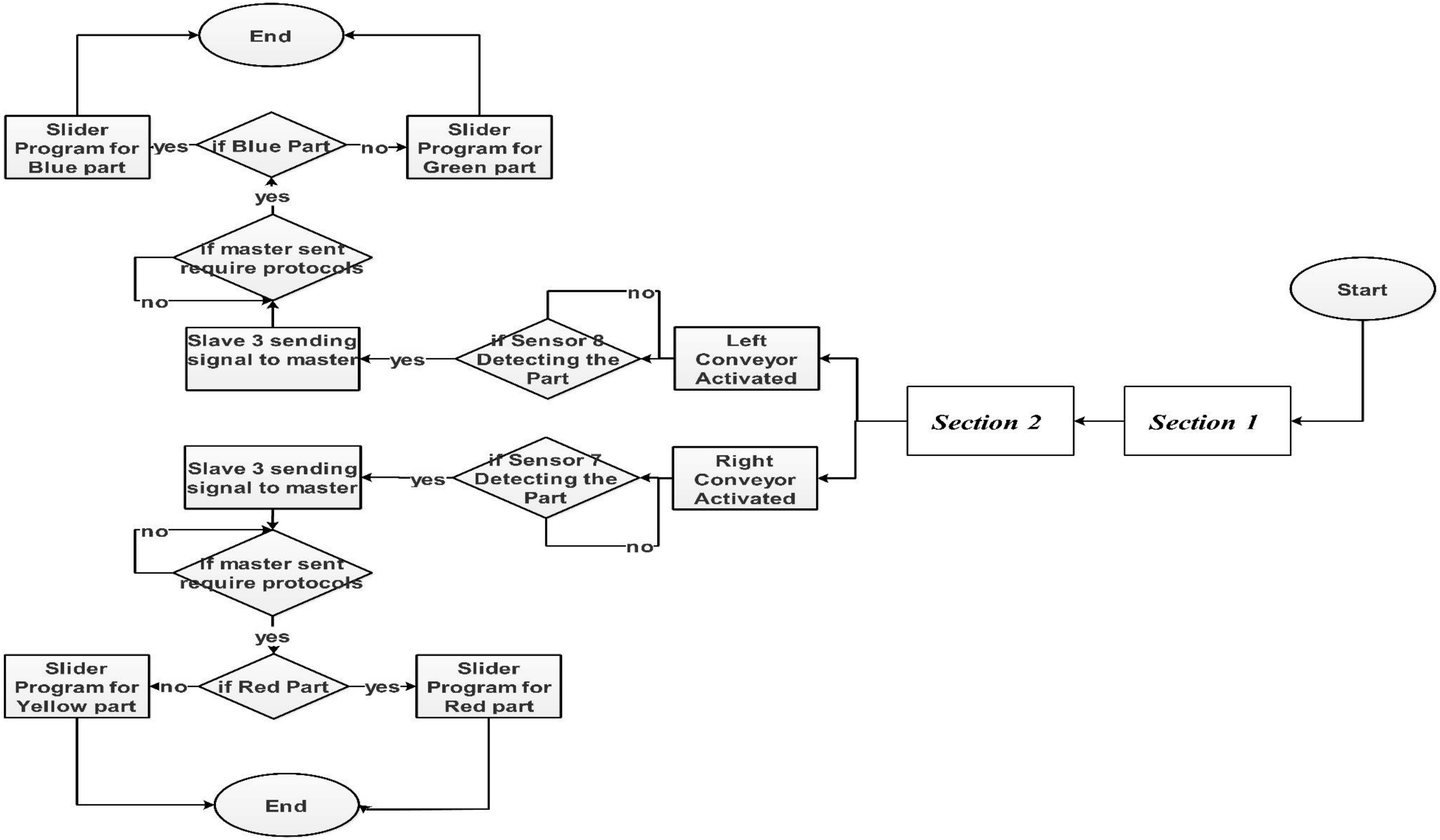


Figure 3.7: Side Conveyors and Sliders Control algorithm (section 3 and 4)

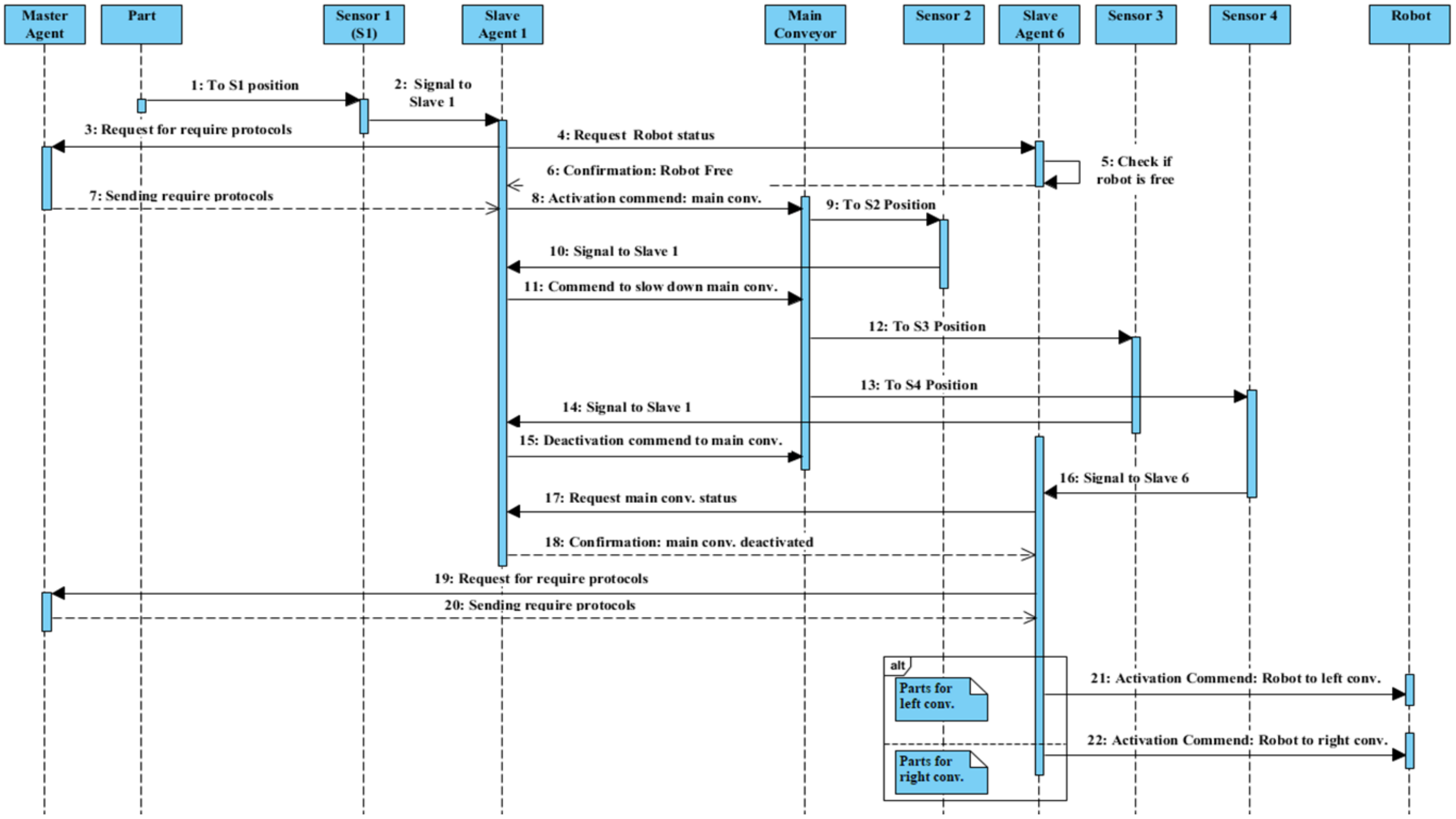


Figure 3.8: Communication algorithm between Slave agent 1 (main conveyor) and Slave agent 6 (robot arm) and Master agent

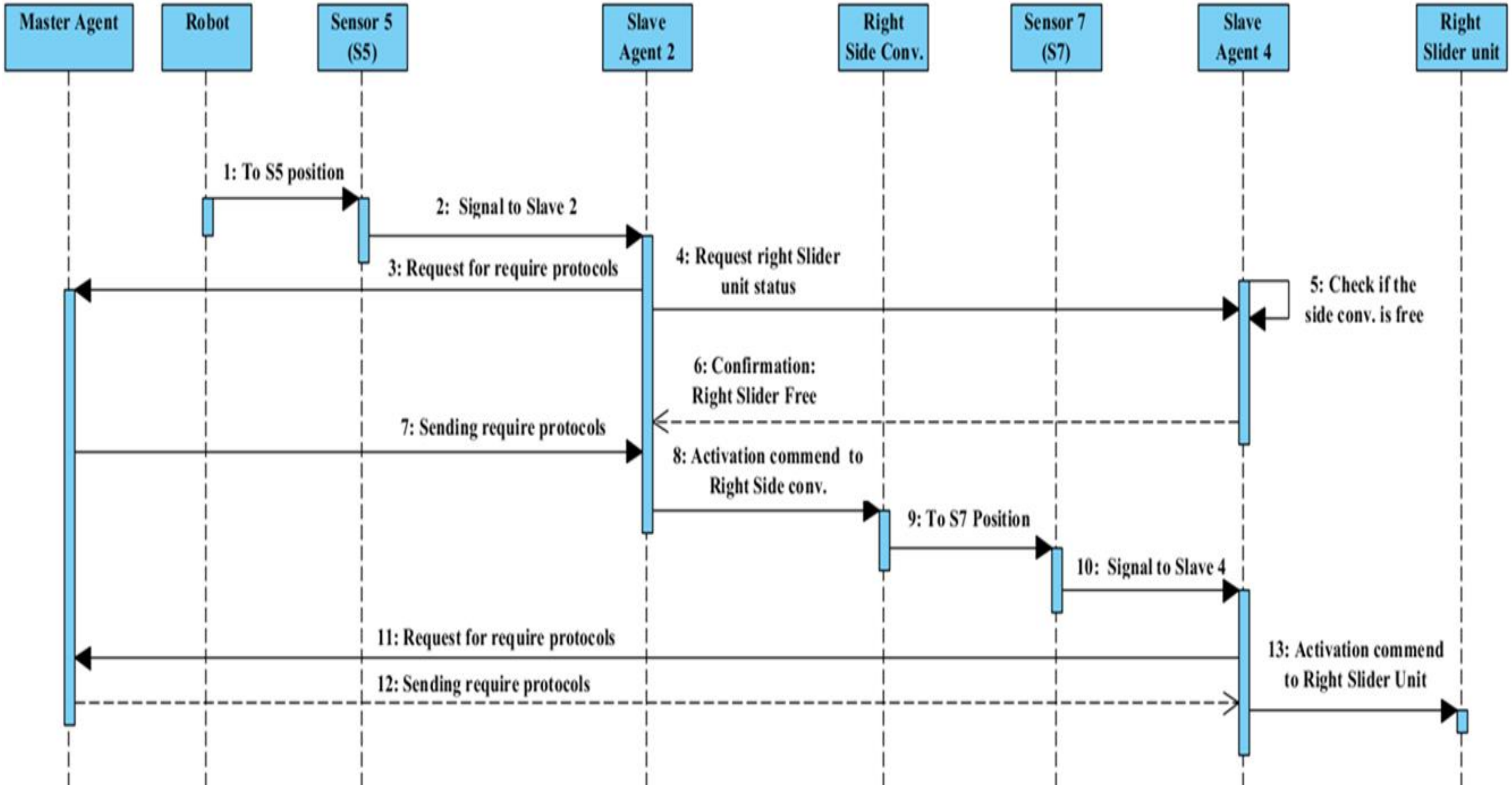


Figure 3.9: Communication algorithm between Slave agent 6 (robot arm), Slave agent 2 (right side conveyor), Slave agent 4 (right slider unit) and Master agent

Same as section 1 and section 2, a communication algorithm between section 2- section 3 and section 2- section 4 were required (Figure 3.9). These algorithms facilitate the collaboration between the following sets of agents:

- Master agent, slave agent 6 (robot arm) and slave agent 2 (right side conveyor).
- Master agent, slave agent 6 (robot arm) and slave agent 3 (left side conveyor).
- Master agent, slave agent 2 (right side conveyor) and slave agent 4 (right sider unit).
- Master agent, slave agent 3 (left side conveyor) and slave agent 5 (left sider unit).

The proposed agent-based algorithm parallel with the communication algorithm make the system able to control the functionality of the resources based on a planned scenario to prevent any overlapping and task conflict between the sections. For instance, slave agent 1 associated with the main conveyor, activating the conveyor for the first time and communicating with slave agent 6 related to the robot arm for reactivation to sending the next part. While the slave agent 6 is activated and busy with its defined task, won’t send the confirmation signal to slave agent 1 until finishing the task. All of the mentioned communications and interaction protocols between the slave agents will be provided and controlled by the master agent.

3.5 Lean Six Sigma strategies to evaluate and improve the performance of the target system after agent-based control architecture

As the main part of the objective for this thesis, the performance of the target manufacturing system (material handling system) after implementation of the proposed agent-based control architecture is evaluated. Furthermore, after evaluation of the performance of the system, limitation and problems of the system were identified. Therefore, for each of the identified problems and limitations, a proper solution was proposed to overcome their negative influences on the performance of the system and improve it accordingly.

In order to reach this goal, Lean Six Sigma-DMAIC strategies were selected as an accurate method to identify and improve the performance of the system. According to the definition of Lean Six Sigma, there are five individual phases which are "Define", "Measure", Analyze", "Improve" and control. To follow the Lean Six Sigma strategies, the required information, data, methods, and tools were defined. This procedure required a comprehensive consideration of the target system properties and characteristics. As the system has been considered as a SMEs, the requirement for each phase of Lean Six Sigma- DMAIC were provided by utilizing the most suitable methods, techniques and standards to obtain the required Information and data (figure 3.10).

3.5.1 “Define” phase of Lean Six Sigma

In order to follow the strategies of “Define” phase of Lean Six Sigma, some essential aspects of the target system were considered. The first considered item was a comprehensive problem statement of the target manufacturing system (material handling system). This problem statement should cover the following items:

- The general definition of the issue/s that the system may face during the process. In the target system, Hardware (manufacturing resources), Software (agent software) and layout design are main categories of the problems and limitations.
- Definition of the manufacturing system resources is the next step has to be done as the requirement of this phase. As the target system in this thesis is an example of SMEs, there are limited numbers of resources which are material handling equipment (conveyors, robot, slider units), measurement equipment (Sensors) and control units (Master and Slaves including their software agents)
- The capability, functionality, and tasks of each resource are also required to be defined in this phase. In the target system, material handling equipment is capable of carrying the material to different sections of the system and distinguishing the material based on the desired plan and control logic. Measurement equipment task is measuring the changes in the physical variables and transfer this data to control units as their required input. Control units are directing the functionality of each resource by providing timing and control signals based on the defined scenario.
- The manufacturing system process plan should be defined which there is a brief statement of how, when and on which order the resources tasks are to be completed. In addition, designate the proper lines of communication and interactions among the resources

- Layout design of the manufacturing system is another aspect which has to be considered as the essential item in the "define" phase of the Lean Six Sigma. Defining the layout includes specifying the coordinates of each resource, its orientation in either a horizontal or vertical position, and the location of its critical points such as load/unload point. For this thesis, the layout design of the target material handling system is shown in figure 3.3.

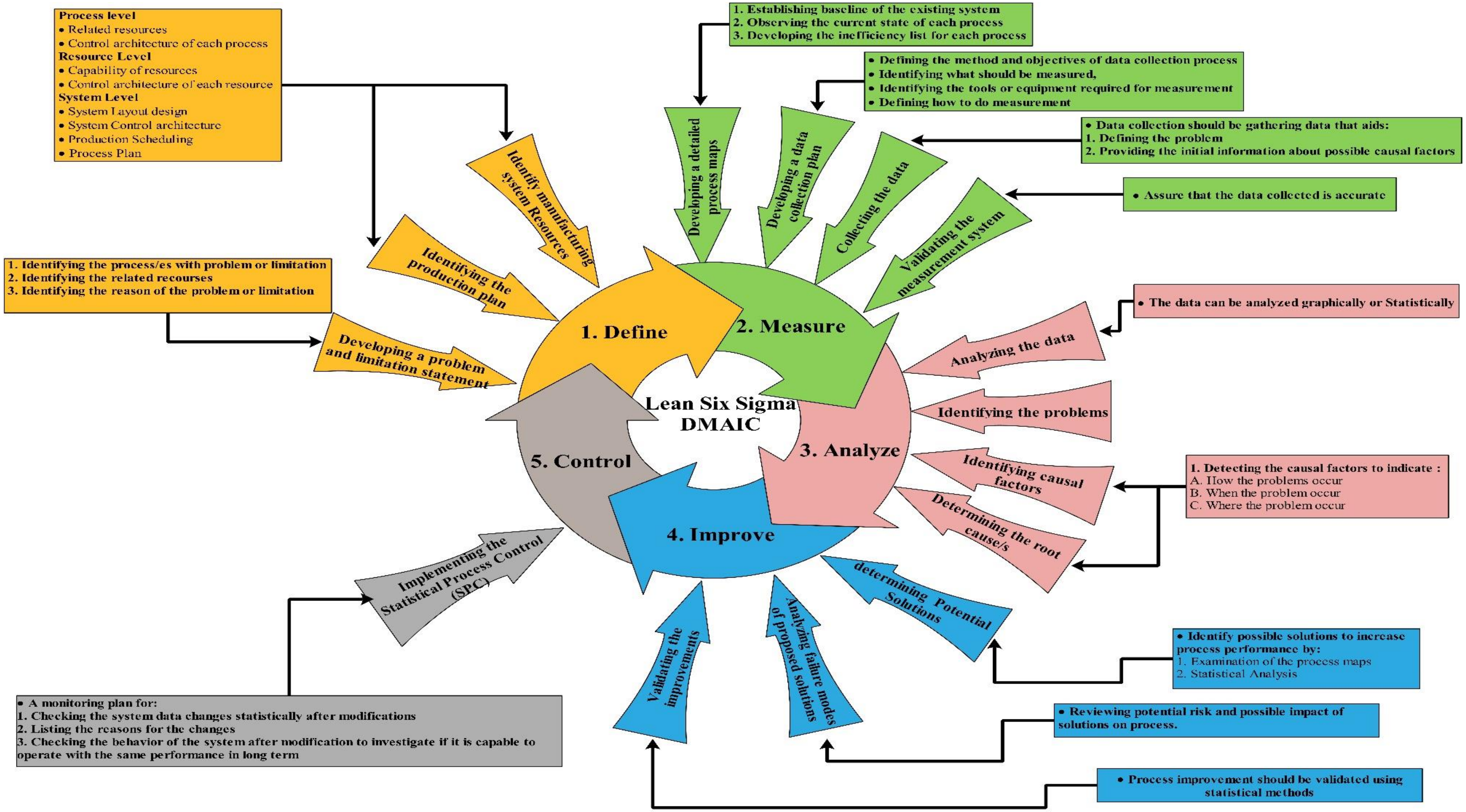


Figure 3.10: Schematic procedure of Lean Six Sigma Implementation

3.5.2 “Measure” phase of Lean Six Sigma

In order to provide the requirements of the “Measure” phase of Lean Six Sigma, developing a comprehensive data collection plan is required. This plan should involve the critical sections of the manufacturing process including the associated resource/s and tasks. This plan helps to identify the process problems, limitations and inefficiencies such as cycle times with long durations, non-value-added tasks, and bottlenecks.

In order to reach this goal in this thesis, the target manufacturing system was divided into individual sections. Each section includes specific resource/s and each resource include specific task/s (Table 3.1). After the definition of the system sections and related task and resources for each section, the objectives of the data collection were defined. These objectives are as follows:

- Identifying what has to be measured
- Selection of proper tools and equipment for the measurement procedure
- Selection of accurate methods and techniques

In this thesis, “Busy time” and “Idle time” of the resources were selected as the factors which have to be measured. These two factors were measured for each section of the system and for each resource during performing the defined task/s. A combined Time study technique was selected which follows the classic time study, MOST and MTM time study techniques. “ProTime Estimation” software has been utilized as the most suitable time study tool which could cover all of the target time study techniques.

Table 3.1: Sections, task description and related resources for the entire scenario

Task	Task Description	Included Resource					
		Main Conv.	Robot	Right Conv.	Left Conv.	Right Slider	Left Slider
1	Main conveyor handling Red object to Robot	✓					
2	Robot arm picking The Red Object from Main Conveyor		✓				
3	Robot arm placing Red object to Right Conveyor		✓				
4	Right conveyor handling Red object to Right Slider			✓			
5	Robot arm moves to its home position after placing Red object		✓				
6	Main conveyor handling Blue object to Robot					✓	
7	Right Slider transfers Red object to Red buffer					✓	
8	Right Slider unloading the Red object to Red buffer					✓	
9	Robot arm picking The Blue Object from Main Conveyor	✓					
10	Robot arm placing Blue object to Left Conveyor		✓				
11	Right Slider moves to its home position after unloading Red object		✓				
12	Left conveyor handling Blue object to Left Slider				✓		
13	Robot arm moves to its home position after placing Blue object		✓				
14	Main conveyor handling Yellow object to Robot						✓
15	Left Slider transfers Blue object to Blue buffer						✓
16	Left Slider unloading the Blue object to Blue buffer						✓
17	Robot arm picking The Yellow Object from Main Conveyor	✓					
18	Left Slider moves to its home position after unloading Blue object		✓				
19	Robot arm placing Yellow object to Right Conveyor		✓				
20	Right conveyor handling Yellow object to Right Slider			✓			
21	Robot arm moves to its home position after placing Yellow object		✓				
22	Main conveyor handling Green object to Robot					✓	
23	Right Slider transfers Yellow object to Yellow buffer					✓	
24	Right Slider unloading the Yellow object to Yellow buffer					✓	
25	Robot arm picking The Green Object from Main Conveyor	✓					
26	Right Slider moves to its home position after unloading yellow object		✓				
27	Robot arm placing Green object to Left Conveyor		✓				
28	Left conveyor handling Green object to Left Slider				✓		
29	Robot arm moves to its home position after placing Green object		✓				
30	Left Slider transfers Green object to Green buffer						✓
31	Left Slider unloading the Green object to Green buffer						✓
32	Left Slider moves to its home position after unloading Green object						✓

3.5.2.1 Time study methodology and data collection

The system was subjected to a time study test by utilizing the "ProTime Estimation" software to investigate the time cycle for each part of the process. The aim to do time study was obtaining the Busy and Idle times for each resource and performing a comprehensive comparison between the resources with the same functionality. Time study of the system helped to identify the resources or tasks with limitations and problems associated with hardware (material handling equipment), software (agent software) and system layout design. These achievements as the result of time study helped to focus on individual resource/s with more problems and limitations and find the proper optimization solutions and methods to improve the performance of the system.

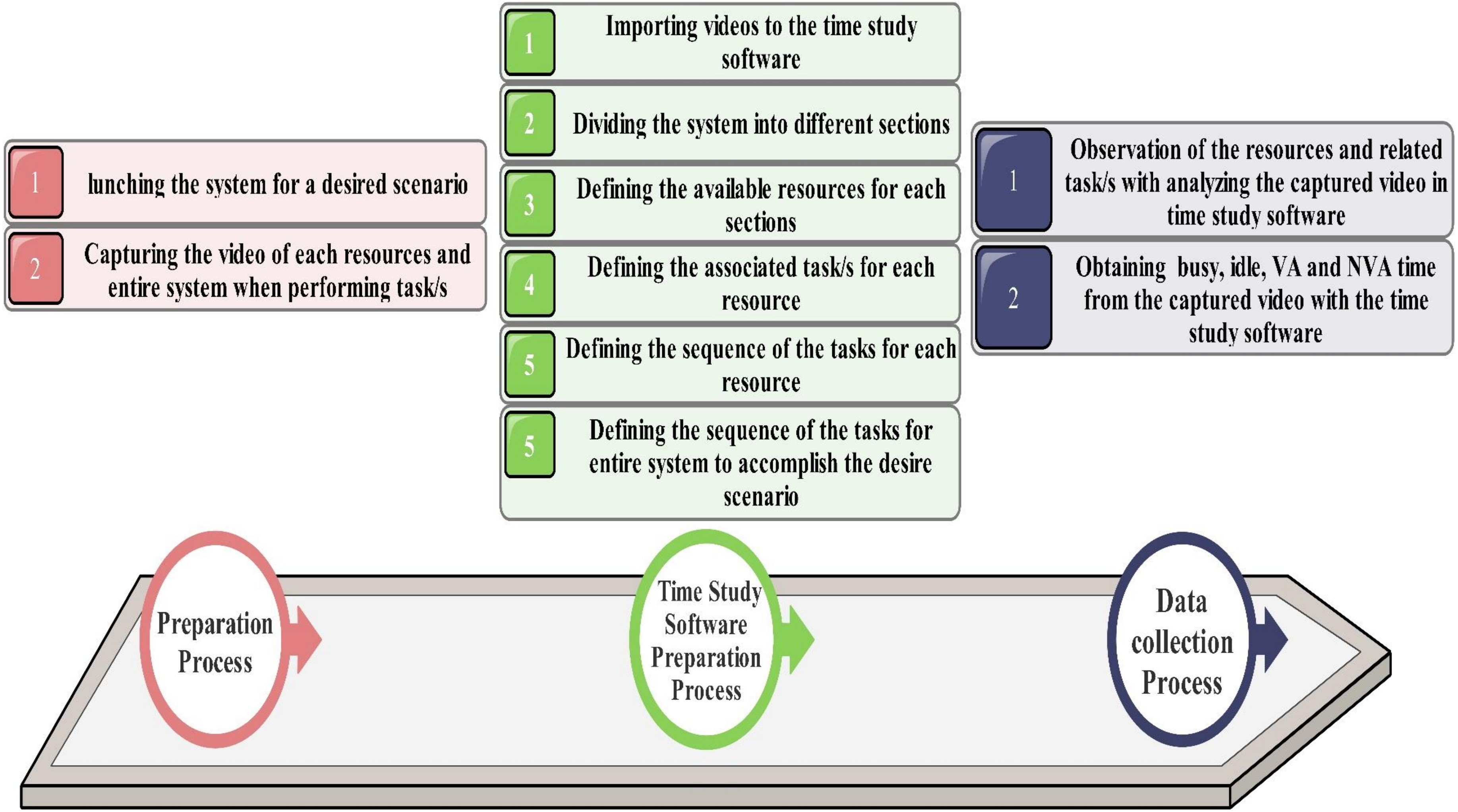


Figure 3.11: Schematic of time study data collection procedure

Figure 3.11 illustrates the time study data collection procedure by utilizing the “ProTime Estimation” software. Three videos files have been captured from different observation view of the system (Right, Left and Front view). The videos were uploaded to the time study software. The time study analysis was performed using the mentioned methodology, where each recorded video was uploaded into the software, and for each video, the mentioned steps were implemented for creating the time study reports (Figure. 3.12). Each of the available tasks labeled with a number (Task Number) and associated resources required to perform that task. These tasks were defined in the ProTime Estimation software. After task definition, the sequence of the tasks (Predecessors) was defined as they were in the real scenario and in the recorded video respectively. The software has the ability to record the start and stop time of each task by a simple procedure. The software makes the operator able to observe the video with different FPS (frames per second) and record the times for each task. In this study, the playing rates were set between 1.0 to 0.6 FPS for getting precise observation and time study data. The ignore, VA, NVA and SVA times were recorded with the aid of the software capabilities (Figure 3.13).

IMG_5534.MOV

Video Stopped 0.00 0.00 / 96.81 Sec

Play Rate: 1.0

Operator: Operator
Study Type: Video

Personal: 0.00 Basic Fatigue: 0.00 Variable Fatigue: 0.00 Special: 0.00

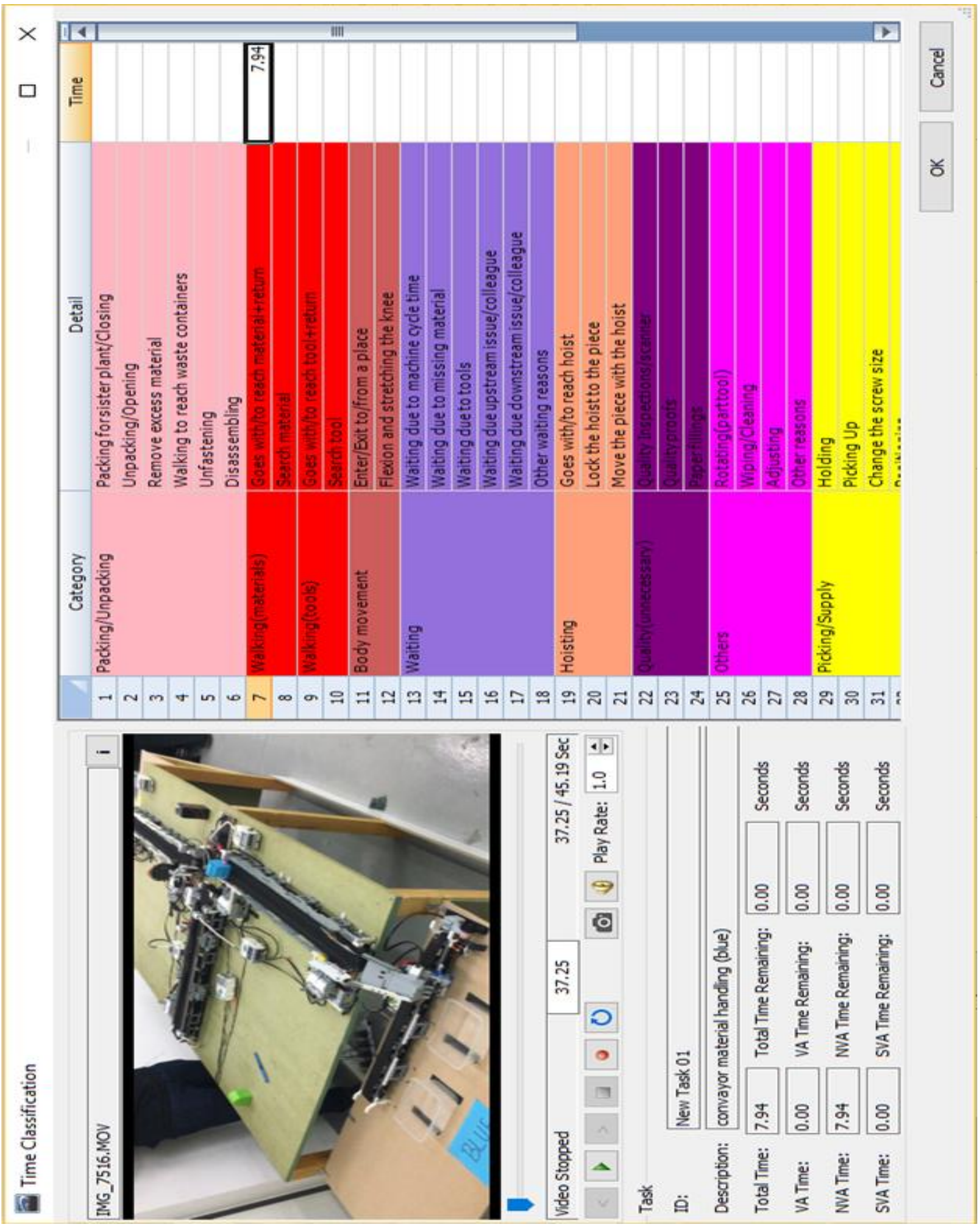
	Order	ID	Desc	Rating	Start	End	Ignore Time	OT	NT	Operator
1	1	New Task 01	convayor to robot (Red)	100	0.03	9.84	0.00	9.81	9.81	Operator
2	2	New Task 05	robot arm material picking	100	9.84	13.39	0.00	3.55	3.55	Operator
3	3	New Task 06	robot arm material placing	100	13.39	16.95	0.00	3.56	3.56	Operator
4	4	New Task 07	robot arm home position	100	16.95	19.57	0.00	2.62	2.62	Operator
5	5	New Task 02	convayor to robot (Blue)	100	19.57	30.40	1.83	9.00	9.00	Operator
6	6	New Task 05	robot arm material picking	100	30.40	34.01	0.00	3.61	3.61	Operator
7	7	New Task 06	robot arm material placing	100	34.01	37.44	0.00	3.43	3.43	Operator
8	8	New Task 07	robot arm home position	100	37.44	40.12	0.00	2.68	2.68	Operator
9	9	New Task 03	convayor to robot (Yellow)	100	43.59	53.71	0.00	10.12	10.12	Operator

File Name	Path
IMG_5534.MOV	C:\Users\Sumilicious\Documents\Uni\Winter2017 LAST\...

	ID	Status	Desc	Task Index	Video	VA
1	New Task 01	Incomplete	convayor to robot (Red)	1	IMG_5534.MOV (Time: 0.03 - 9.84)	
2	New Task 02	Incomplete	convayor to robot (Blue)	2	IMG_5534.MOV (Time: 19.57 - 30.40)	
3	New Task 03	Incomplete	convayor to robot (Yellow)	3	IMG_5534.MOV (Time: 43.59 - 53.71)	
4	New Task 04	Incomplete	convayor to robot (Green)	4	IMG_5534.MOV (Time: 63.50 - 74.20)	
5	New Task 05	Incomplete	robot arm material picking	5	IMG_5534.MOV (Time: 9.84 - 13.39)	
6	New Task 06	Incomplete	robot arm material placing	6	IMG_5534.MOV (Time: 13.39 - 16.95)	
7	New Task 07	Incomplete	robot arm home position	7	IMG_5534.MOV (Time: 16.95 - 19.57)	

Figure 3.12: Time study software GUI

The time study report for each task and each section of the system were generated associated with each resource/material individually. Data from each section of the system (left, Right and Front) were combined to generate a comprehensive time study report of the system.



IMG_7516.MOV

Video Stopped 37.25 37.25 / 45.19 Sec

Play Rate: 1.0

Task

ID: New Task 01

Description: convayor material handling (blue)

Total Time: 7.94 Total Time Remaining: 0.00 Seconds

VA Time: 0.00 VA Time Remaining: 0.00 Seconds

NVA Time: 7.94 NVA Time Remaining: 0.00 Seconds

SVA Time: 0.00 SVA Time Remaining: 0.00 Seconds

	Category	Detail	Time
1	Packing/Unpacking	Packing for sister plant/Closing	
2		Unpacking/Opening	
3		Remove excess material	
4		Walking to reach waste containers	
5		Unfastening	
6		Disassembling	
7	Walking(materials)	Goes with/to reach material+return	7.94
8		Search material	
9	Walking(tools)	Goes with/to reach tool+return	
10		Search tool	
11	Body movement	Enter/Exit to/from a place	
12		Flexion and stretching the knee	
13	Waiting	Waiting due to machine cycle time	
14		Waiting due to missing material	
15		Waiting due to tools	
16		Waiting due upstream issue/colleague	
17		Waiting due downstream issue/colleague	
18		Other waiting reasons	
19	Hoisting	Goes with/to reach hoist	
20		Lock the hoist to the piece	
21		Move the piece with the hoist	
22	Quality(unnecessary)	Quality inspections/scanner	
23		Quality proofs	
24		Paper fillings	
25	Others	Rotating(part tool)	
26		Wiping/Cleaning	
27		Adjusting	
28		Other reasons	
29	Picking/Supply	Holding	
30		Picking Up	
31		Change the screw size	

Figure 3.13: Value added, Non-Value added and Semi-Value-added times definite

3.5.3 "Analyze" phase of Lean Six Sigma

In the “Measure” phase of Lean Six Sigma, a time study report was generated which provided required information to identify the problems, limitations and associated resources. In “Analyze” phase of Lean Six Sigma, this time study report was analyzed to obtain causal factors. Obtaining the causal factors associated with each problem and limitation helps to identify the following:

- Exact moment for problems occurrence
- The resource/s and associated task/s in which the problems and limitations occurred
- The reason behind the problems and limitation occurrence.

These causal factors affecting the performance of the system by affecting on each resource and associate task/s. Therefore, it was essential to utilize an accurate technique including standards to evaluate the performance of the system. This technique must have the capability of performance evaluation partially for each task, resource, and the entire system. Thus, Overall Equipment Effectiveness (OEE) was selected as the most efficient technique to evaluate the performance of the system.

3.5.3.1 Overall Equipment Effectiveness and performance evaluation

In order to calculate the OEE, there are three OEE Factors which was required to be calculated individually. "Availability" was the first OEE factor which is the ratio of "Run Time" to "Planned Production Time" (Equation 3.1).

$$\text{Availability} = \text{Run Time} / \text{Planned Production Time} \qquad \text{(Equation 3.1)}$$

To calculate the "Planned Production Time", scheduled losses which in this thesis were considered as "Idle time", was subtracted from the "Cycle Time" (Equation 3.2).

$$\text{Planned Production Time} = \text{Cycle time} - \text{Idle time} \qquad \text{(Equation 3.2)}$$

"Run time" is "Planned Production Time" without Stop Time (Downtime) which is all time where the system was expected to be running but was not because of the unplanned Stops such as breakdowns (Equation 3.3).

$$\text{Run Time} = \text{Planned Production Time} - \text{Down Time} \qquad \text{(Equation 3.3)}$$

The second OEE factor is "Performance" and includes anything which prevents a resource to operate at less than the maximum possible speed. Performance is the ratio of “Ideal Cycle time” and “Total Count” to “Run Time” (Equation 3.4).

$$\text{Performance} = (\text{Ideal Cycle time X Total Count}) / \text{Run time} \qquad \text{(Equation 3.4)}$$

In this thesis “Ideal Cycle Time” considered as the minimum time to accomplish task/s for a product in each resource theoretically. For instance, the minimum time for a part to move on the main conveyor to reach to a point which the robot arm can pick it up. This time has been calculated based on the conveyor length and speed theoretically. In addition, “Total Count” is the total number of the part/s which a task associated with resource/s was accomplished for each of them.

The last OEE factor is “Quality” which was calculated as the ratio of “Good Count” to “Total Count”. In this thesis, due to the characteristic of the target system (Educational System) and associated production plan, all of the parts were considered as “Good Count” without defect. However, as it has been mentioned before the main task for the system is to distinguish the products with passed quality control (Equation 3.5).

$$\text{Quality} = \text{Good Count} / \text{Total Count} \qquad \text{(Equation 3.5)}$$

3.5.4 "Improve" phase of Lean Six Sigma

In this phase of Lean Six Sigma, the identified problem, limitations and associated causal factors in the previous phase were investigated to obtain all the possible solutions. It was expected to gain better system performance after the implementation of these solutions. However, due to the characteristic of the target system, implementation of these solutions without ensuring their effects on the system performance was critical as it has been mentioned in chapter one. Therefore, validation of each of the solution to overcome the problems and limitations to improve the performance of the system was required. To reach this goal, a discrete event simulation was utilized to verify the effect of the solutions on the performance of each resource and the entire system.

3.5.4.1 The Simulation model to verify the solutions for improving the system performance

To build the simulation model of the target system in Arena, primary features of the system such as resources, processes, variables, and attributes are playing an important role. After the definition of these features, the simulation model algorithm was generated by utilizing Arena's flowchart modeling methodology. The Functional Specification of the system was utilized as the roadmap for the model to ensure that the model was developed correctly to address the problem. In addition, the simulation model needs some data which was needed to be collected manually via time studies, work sampling, etc. form the real system such as the speed of the motions and distances between resources.

Once a simulation model with the same feature of the real system was created, it was required to ensure that the model behaviors and functionality were completely matched with the real system by collecting the simulation data. In order to generate the simulation database, it was necessary to identifying the type of required data and determining where this data comes from.

Validation of the simulation model reliability is based on user's approval with analyzing the simulation model data. If the data is close enough to the real system data, it is reliable enough to be modified based on the identified solutions to improve the system performance. In this thesis, the model inputs are actual data from the real system and the simulation model data will be compared with time study result of the real system. In all cases, the changes in the existing system are amended to reflect on the simulation model for continues analysis and operational decision making.

3.5.5 "Control" phase of Six Sigma

In the "Control" phase of Lean Six Sigma maintaining and supporting the gains during the "Improve" phase was the main aim. In this phase, a comprehensive investigation was needed to identify the solutions and associated factors which affect more on the system performance. Categorizing the solutions and factors helps in considering the priorities for each solution and associated factor. In this thesis, several solutions were defined for each resource and three factors which affect more on the system performance were selected which were the distance between the resources, speed of motion for each resource and the system layout design. For each resource, a priority was given to these factors based on their effectiveness on the resource and entire system performance.

Chapter 4

RESULT AND DISCUSSION

4.1 Overview

In this chapter, the results of the study are presented and discussed with reference to the aim of the study and objectives. The main aim was to determine the performance of the system after the implementation of the novel agent-based control architecture by following the Lean Six Sigma-DMAIC strategies and utilizing time study technique and Overall Equipment Effectiveness standard. In the “analyze” phase of Lean Six Sigma, some problems and limitations associated with the target system were identified and possible solutions were suggested. To evaluate the impact of the solution on system performance, a simulation model of the system was created. The system performance was evaluated by utilizing the simulation results and compared with the performance of the system before the implementation of the solutions. Out of the proposed solutions, the ones with more impact on the performance of the system were identified to generate a priority list for each one of them to rich to the highest system performance.

4.2 Discrete time study results for each phase of the system

In order to follow the requirement of “Measure” phase of Lean Six Sigma strategy and based on the defined phases and associated resource/s for the target system, a time study was performed for each phase individually. By collecting the time study result from each phase, an inclusive time study data for the entire system was obtained which was required for the "Analyze" phase of Lean Six Sigma. Discrete time study helped to identify the problems and limitations related to each phase by addressing the associated recourse/s in which the problem occurred.

4.2.1 Time study result of the main conveyor

The first step of time study was done on the main conveyor and the robot arm, which contains the specific tasks as shown in table 4.1. Figure 4.1 shows the Utilization Gantt chart of the main conveyor. The moment of the first object (red object) placement on the conveyor, was considered as the onset of the time study. When the motion sensor detected the first object, the conveyor started moving for 9.81 seconds and the object reached the color sensor position located the end of the main conveyor. Thence, the robot picked up the object after the color sensor detected the red object. The conveyor was on idle mode for 9.73 seconds while the robot arm was active for picking up the object from the main conveyor and placing it on the side conveyor. Once the red object was placed on the right side-conveyor, the main conveyor activated and moved the blue object for 9.04 seconds to reach the point in which the robot arm could pick it up. The process was repeated for the yellow and green objects in the same manner. The main conveyor idle time before moving the yellow and green object was 10.48 and 10.25 seconds respectively. In addition, 9.86 seconds for yellow object and 9.62 seconds for green object took for the main conveyor to deliver them to the robot arm (Table 4.1).

Figure 4.1 and table 4.1 for the main conveyor show the different busy and idle time associated with each object. It is with considering that the same values were expected due to the utilization of the same device (main conveyor) and handling process. The lowest recorded time was related to the blue object and it indicated that the delivery of this part to the robot by the main conveyor was faster than the order objects.

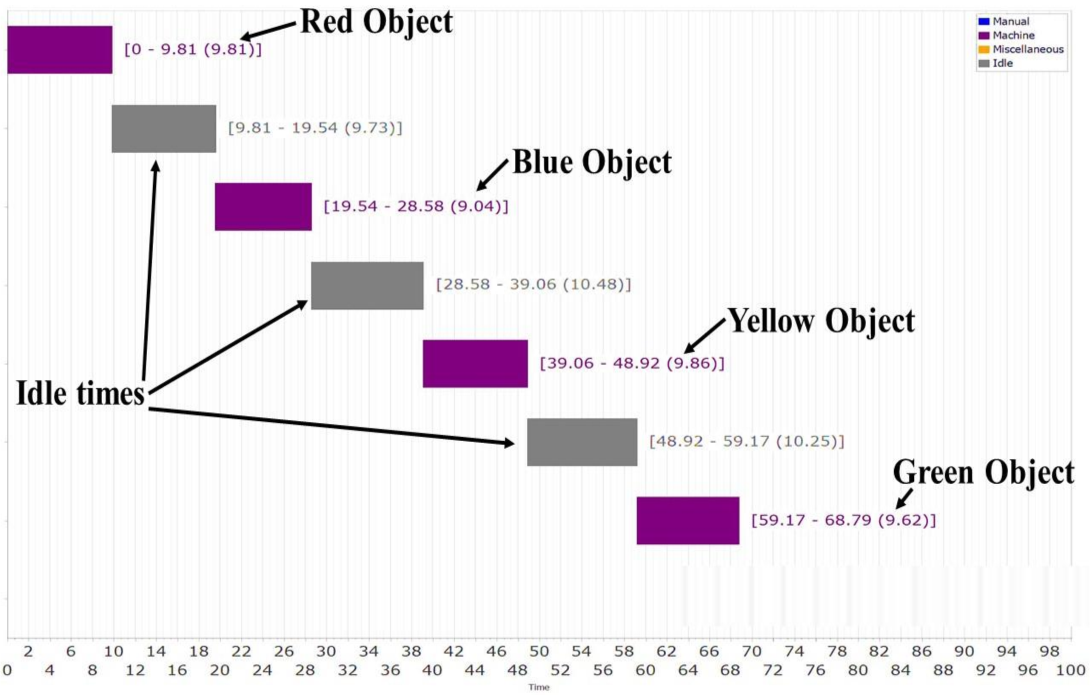


Figure 4.1: Main conveyor utilization report

Table 4.1: Main conveyor Time study data

Task description	Start (s)	End (s)	Busy Time (s)	Idle time (s)
Main conveyor handling Red object to Robot	**0**	**9.81**	**9.81**	**9.73**
Main conveyor handling Blue object to Robot	**19.54**	**28.58**	**9.04**	**10.48**
Main conveyor handling Yellow object to Robot	**39.06**	**48.92**	**9.86**	**10.25**
Main conveyor handling Green object to Robot	**59.17**	**68.79**	**9.62**	**-**

4.2.1.1 Identified problem and limitation for the main conveyor by time study and possible solutions

In order to follow the "Analyze" phase of Lean Six Sigma strategies and with utilizing the time study report associated with the main conveyor, all the problems, limitation and possible solution for this resource have been identified. All of the detected problems related to the main conveyor caused by the control software in slave agent 1 and its interaction with slave agent 6.

The busy time difference for moving the objects caused by the definition of the detection range of sensors to activate the conveyor in slave agent 1. It means, by modification of the detection range, sensors can identify the objects and sending the signal faster to the slave agent 1, no matter how the parts are placed on the conveyor.

The difference between idle times was mainly depending on the color sensor and robot performance respectively. By modification of the light intensity detection range for the color sensor on slave agent 6, the color of part can be detected faster and slave agent 6 can activate the robot faster, no matter where the parts are detecting in the covered area of the color sensor.

Slave agent 1 was not able to be activated before receiving the signal which was about the robot arm task accomplishment from slave agent 6. Therefore, to reduce the idle time, it was important to optimize the speed of the robot motion as it was affecting the conveyor idle time.

In general, increasing the speed of motion and decreasing the distance between the resources aiming at reducing the time is possible with increasing the power range of the available motors associated to the resource which would be possible by modification of the agent software on slave agent 1 and 6. On the other hand modifying the layout design between the main conveyor and robot arm aiming at decreasing the distance, resulting in decreasing the time between these two resources. For instance, locating the color sensor (sensor 4) closer to the sensor 2, increasing the ability of the slave agent 6 to analyze the signal and decide to transfer the part to left or right side conveyor based on the color.

4.2.2 Time study result of the robot arm

The robot arm process was steady and the values of picking and placing each object were nearly the same. Table 4.2 shows the start, end, and total time of the robot arm tasks. Table 4.2 also noticed that the process was steady except for the blue object. The table also shows that the idle time for robots is equal to the busy times for the main conveyor. It means the robot was on idle model while the main conveyor moved the parts.

4.2.2.1 Identified problem and limitation for robot arm by time study and possible solutions

The different busy time for the robot to move the blue part indicated that the color sensor had difficulty in recognizing the object and blue color on time. Consequently, agent software including the definition of light intensity detection range for this sensor in slave agent 6 must be modified to be able to recognize the objects with different color more accurate. Figure 4.2 shows that the idle times of the robot arm are depending on the main conveyor process. As a result, reducing the idle time of the robot arm can be achieved by increasing the efficiency of the process of the main conveyor as mentioned before.

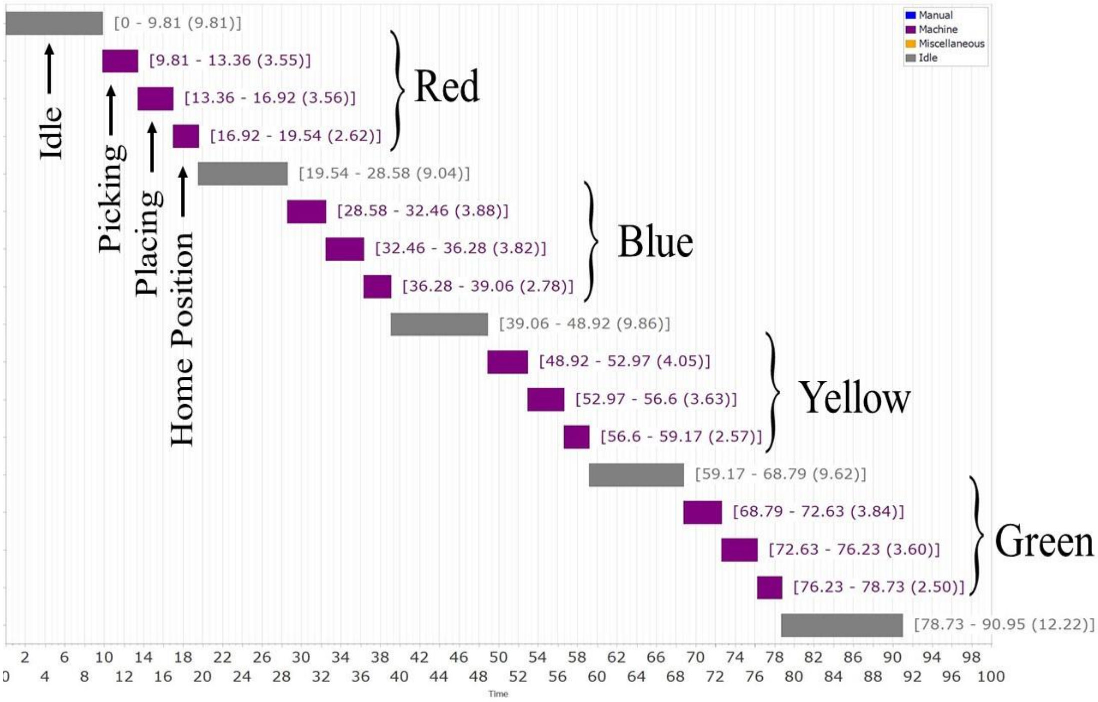


Figure 4.2: Robot arm utilization report

Table 4.2: Robot arm time study report

Task description	Start (s)	End (s)	Busy time (s)	Idle Time (s)
red object picking	9.843	13.36	3.55	
red object placing	13.36	16.92	3.56	
robot arm home position	16.92	19.54	2.62	
Busy and Idle time for Red Object			**9.73**	**9.81**
blue object picking	28.58	32.46	3.88	
blue object placing	32.46	36.28	3.82	
robot arm home position	36.28	39.06	2.78	
Busy and Idle time for Blue Object			**10.48**	**9.04**
yellow object picking	48.92	52.97	4.05	
yellow object placing	52.94	56.60	3.36	
robot arm home position	56.60	59.17	2.57	
Busy and Idle time for Yellow Object			**9.98**	**9.84**
green object picking	68.79	72.63	3.84	
green object placing	72.63	76.23	3.60	
robot arm home position	76.23	78.73	2.50	
Busy and Idle time for Green Object			**9.94**	**9.62**

4.2.3 Time study result of the right side-conveyor

Table 4.3 illustrates 50.29 second overall idle time to move the red and yellow objects by right side-conveyor to right slider unit. Right side-conveyor was on idle mode to receive the red object for 16.92 seconds, whereas 33.37 seconds to receive the yellow object. There were 22.15 seconds as idle time in which the right side-conveyor was on idle mode and waiting for whole the process to be done. The idle time for this conveyor is combined the time that this conveyor should be on idle mode and wait for main conveyor and robot to do its tasks. For example, the idle time before moving the red object is 16.92 second which is the summation of 9.81 seconds as a busy time for the main conveyor to move this object and 3.55 and 3.56 second for the robot arm to pick the part from the main conveyor and place it on right side-conveyor.

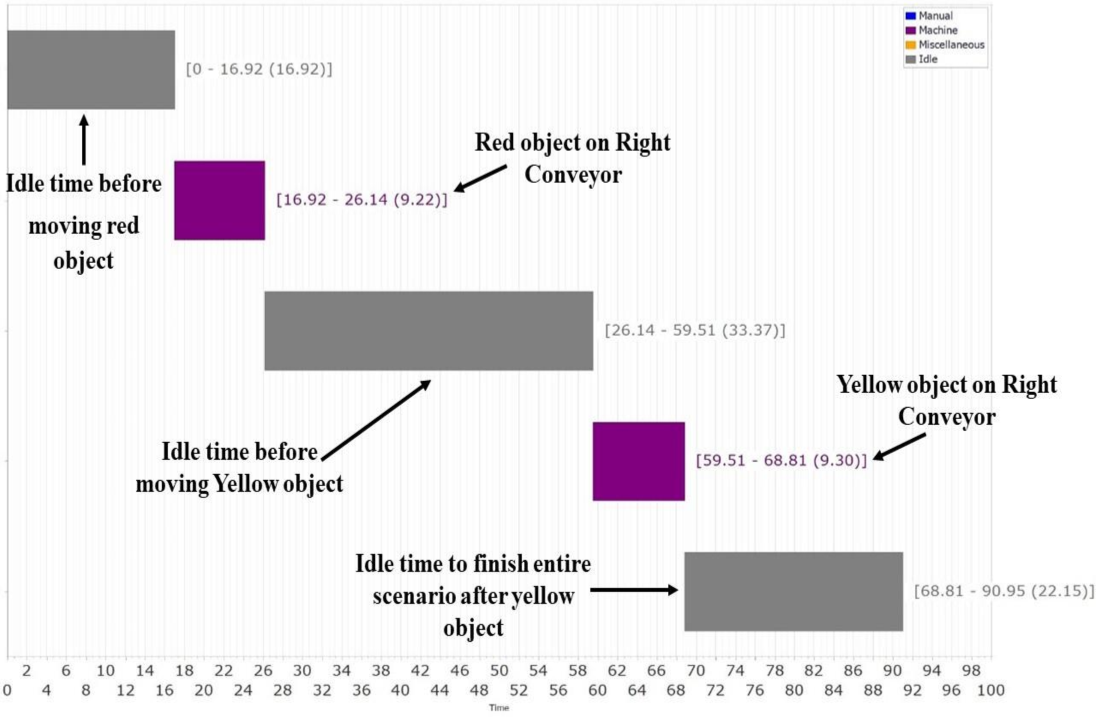


Figure 4.3: Right side-conveyor utilization report

Table 4.3: Right side-conveyors time study data

Task description	Start (S)	End (s)	Busy time (s)	Idle time (s)
Right side-conveyor Idle time before moving red object				16.92
Right side-conveyor for the red object	16.92	26.14	9.22	
Right side-conveyor Idle time before moving Yellow object				33.37
Right side-conveyor for Yellow Object	59.51	68.81	9.30	
Overall Busy and Idle time for Right side-conveyor			**18.52**	**50.29**
Right side-conveyor Idle time after moving Yellow object				22.15

4.2.3.1 Identified problem and limitation for right side-conveyor by time study and possible solutions

Focusing the time study result of side-conveyor in table 4.3 confirms that the busy time for this resource is less than the time spent as idle or non-value added time. Decreasing the idle time will result in increasing the performance of the conveyor. It is noteworthy to mention that this resource was like a link between the main conveyor and right slider unit and performance of the resources in between affecting the performance of the side conveyor. Therefore, increasing the performance of the main conveyor, robot and right slider unit will decrease the idle time for right side conveyor. However, the software agent in slave agent 1, 2, 4 and 6 should be modified about control logic and communication among these slave and master agents. Furthermore, changing the layout design to increase the access and exit point (the point in which the right side-conveyor connecting to the slider) could be an adequate solution.

4.2.4 Time study result of the right slider unit

Figure 4.4 shows that the right slider was in idle mode during the experiment and in time study result, idle time is more than the busy time for this resource. This resource has three main tasks which are moving the object to the target buffer (Buffer for red and objects), unloading the object to the buffers and moving back to its initial position (home). The summation of the time spent on these tasks has been considered as busy time. Due to the different behavior of the system for moving the red object and yellow object, time study was done for each process individually. This slider was on idle mode for 26.14 seconds before moving the red object and process of moving the object to buffer and going back to home position took 12.49 second (Table 4.4).

Since the distance between the buffers associated with red and yellow objects was different, the busy time differs to move these objects. The sliders have unloading task which is the task related to a mechanism inside the slider to unload the objects to the buffer. The busy time for unloading task associated with both objects is nearly the same and it is 4.50 second and 4.32 second for red and yellow objects respectively. In addition, the busy time to move the objects to the related buffer is 3.97 second for red object and 0.99 seconds for the yellow one. The busy time for the slider to move back to the home position is dramatically different due to the distance between buffers (Table 4.4).

4.2.4.1 Identified problem and limitation for right slider by time study and possible solutions

The idle time for this resource is affecting by the performance of the previous resources (main conveyor, robot arm and right side-conveyor) to deliver the object to this slider. In order to reduce the idle time for the slider unit, the performance of the mentioned resources should be optimized. To reach this aim, the agent software in Slave agents 1, 2 and 6 should be modified and the proposed solution in the previous section should be performed on these resources.

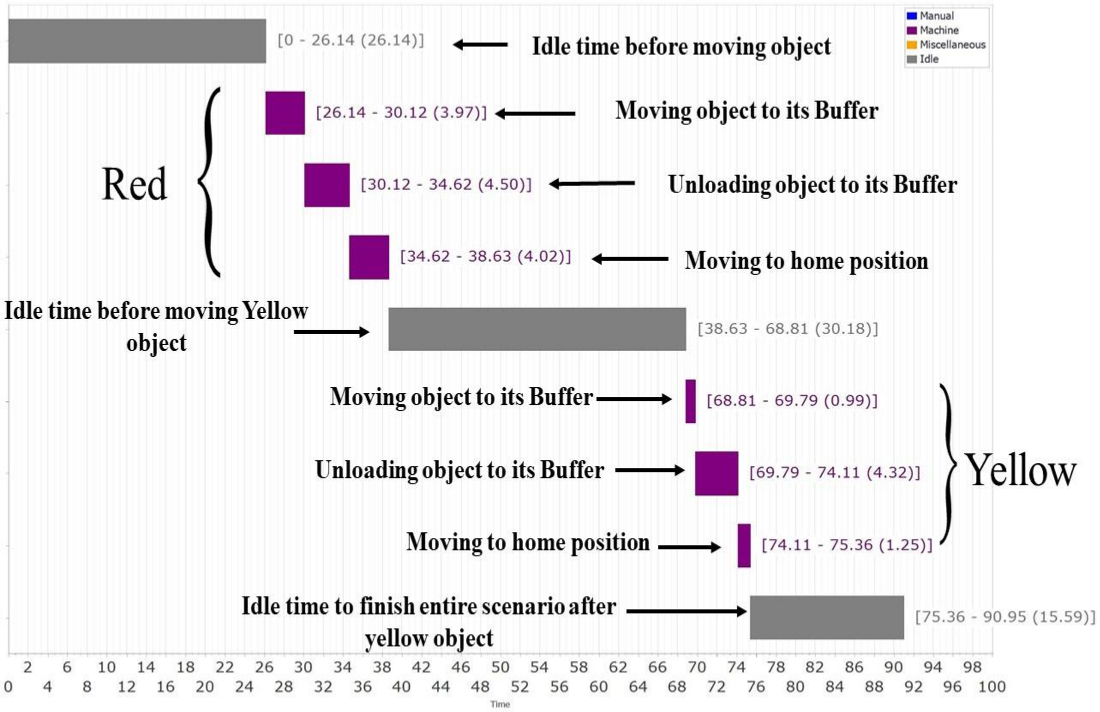


Figure 4.4: Right slider utilization report

Table 4.4: Right sliders time study data

Task description	Start (S)	End (s)	Busy time (s)	Idle time (s)
Right slider Idle time before moving red object				26.14
Right slider to Red buffer	26.14	30.12	3.97	
Right slider unloading red	30.12	34.62	4.50	
Slider home position after unloading red	34.62	38.63	4.02	
Overall Busy and Idle time for Right side-conveyor to move red object			**12.49**	**26.14**
Right slider Idle time before moving yellow object				30.18
Right slider to yellow buffer	68.81	69.79	0.99	
Right slider unloading yellow	69.79	74.11	4.32	
Slider home position after unloading yellow	74.11	75.36	1.25	
Overall Busy and Idle time for Right side-conveyor to move yellow object			**6.56**	**30.18**
Right slider Idle time after moving red object				15.59

4.2.5 Time study result of the Left side-conveyor and left slider unit

Since the functionality and hardware design of the left side-conveyor and left slider unit is the same as the right conveyor and slider, the same analysis applies on their time study results(Figure 4.5 and 4.6). Total idle time for left side-conveyor is 68.29 seconds and for left slider unit is 46.57 second and 24.60 seconds for blue and green objects respectively. (Table. 4.5 and 4.6). The busy time associated with left side-conveyor for moving the blue and green objects is nearly the same and it is 7.94 second and 7.88 seconds respectively. The time study result for the left slider has the same pattern as it was in the right one. It means the left slider for moving the blue object has nearly the same value as it was in the right slider for red object and yellow same as green respectively. Also, nearly the same time for moving back to the home position after unloading the objects.

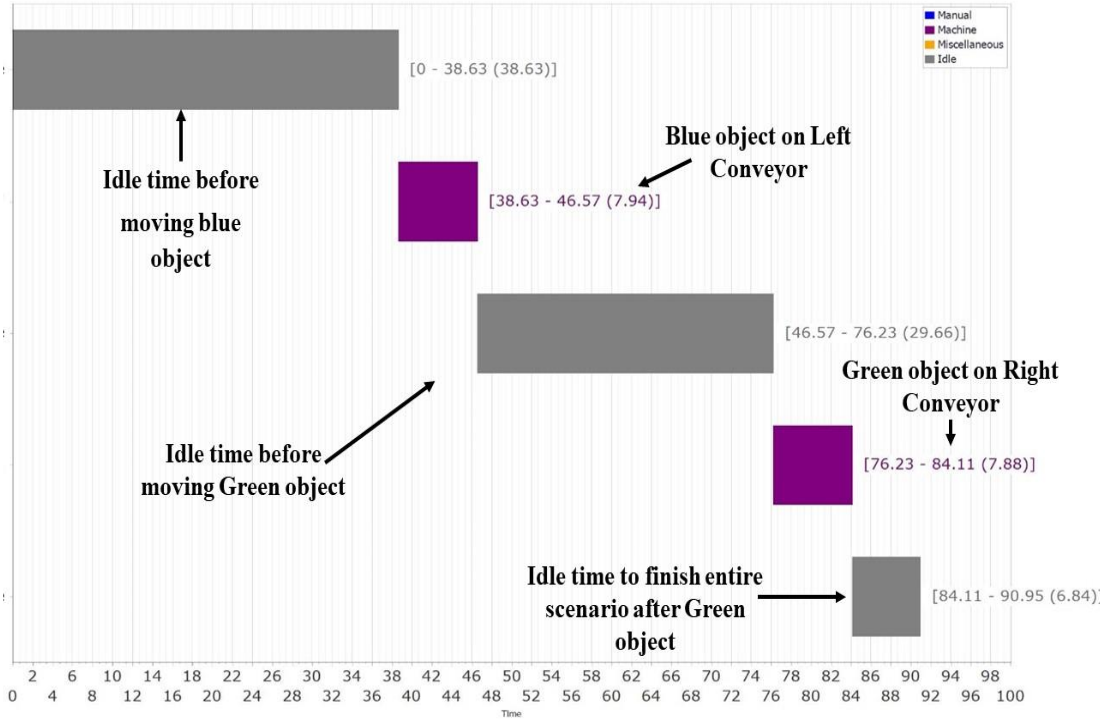


Figure 4.5: Left side-conveyor utilization report

Table 4.5: Left side-conveyor time study data

Task description	**Start (S)**	**End (s)**	**Busy time (s)**	**Idle time (s)**
Left side-conveyor Idle time before moving blue object				38.63
Left side-conveyor for blue object	38.63	46.57	7.94	
Left side-conveyor Idle time before moving Green object				29.66
Left side-conveyor for Green Object	76.23	84.11	7.88	
Overall Busy and Idle time for Left side-conveyor			**15.82**	**68.29**
Left side-conveyor Idle time after moving Green object				6.84

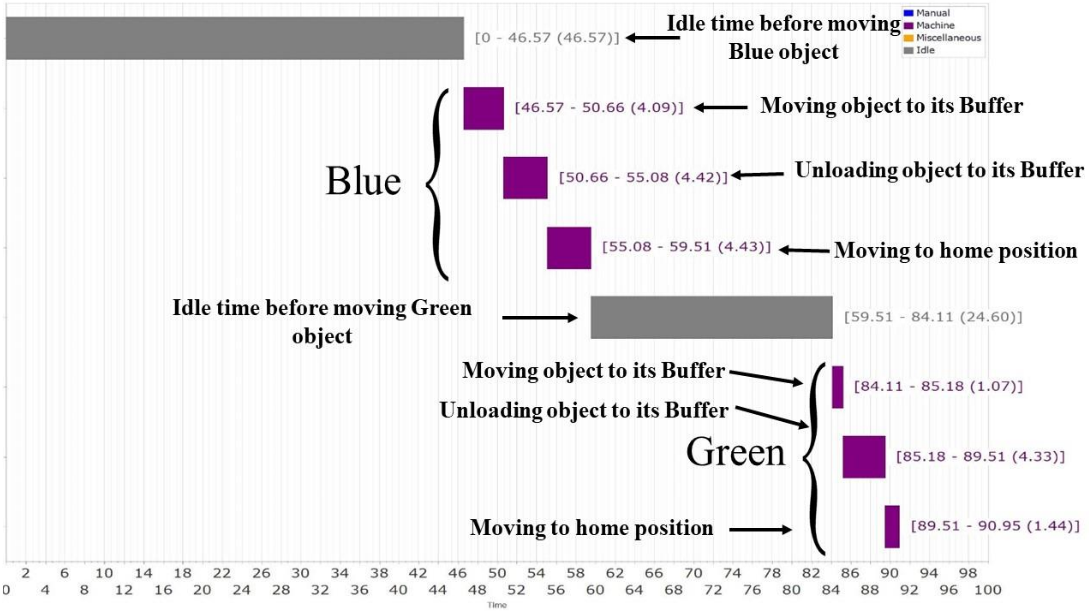


Figure 4.6: Left slider utilization report

Table 4.6: Left slider time study data

Task description	**Start (S)**	**End (s)**	**Busy time (s)**	**Idle time (s)**
Left slider Idle time before moving blue object				46.57
Left slider to blue buffer	46.57	50.66	4.09	
Left slider unloading blue	50.66	55.08	4.42	
Slider home position after unloading blue	55.08	59.51	4.43	
Overall Busy and Idle time for Left side-conveyor to move the blue object			**12.94**	**46.57**
Left slider Idle time before moving green object				24.60
Left slider to green buffer	84.11	85.18	1.07	
Left slider unloading green	85.18	89.51	4.33	
Slider home position after unloading green	86.51	90.95	1.44	
Overall Busy and Idle time for Left side-conveyor to move the green object			**6.84**	**24.60**

4.2.6 Comparison between left and right side-conveyor time study results

The right side-conveyor (assigned for Red and Yellow objects) spends greater time in moving the objects to the slider, whereas the left conveyor (assigned for Green and Blue objects) spends less time by 2.7 seconds. Since the same expectation, hardware design and same architecture for software agents in slaves for these conveyors, it has been thought the values were incorrect. This led to taking additional videos and repeating time study to evaluate the conveyor performance again. After applying an accurate time study, especially for this section and evaluating the data, it turned out that the conveyors were designed with different lengths (Right Conveyor 10 cm Longer than Left one) and the times recorded are correct. Therefore, this great value difference is correct because of the additional length of the right conveyor.

4.2.7 Comparison between left and right slider unit time study results

The time study result shows the similar behavior of slider for moving the red and blue objects as well as green and yellow objects. Since the distances to buffers for sliders to move the parts and move back to the home position are same, the busy time for blue and red objects and yellow and green objects are the same respectively. Therefore, the slight difference in the values was because of the light intensity range of color sensor detection and its time delay which were defined in slave agent 4 and 5.

4.2.8 Overall time study result of the entire system

The following Gantt chart (Figure 4.7) and Table 4.4 illustrate the time study report for the entire system, showing the busy and idle time of each resource and the behavior of two or more resources are working at the same time. The Gantt chart was generated using the tasks dependencies table (Table 4.5 and 4.6).

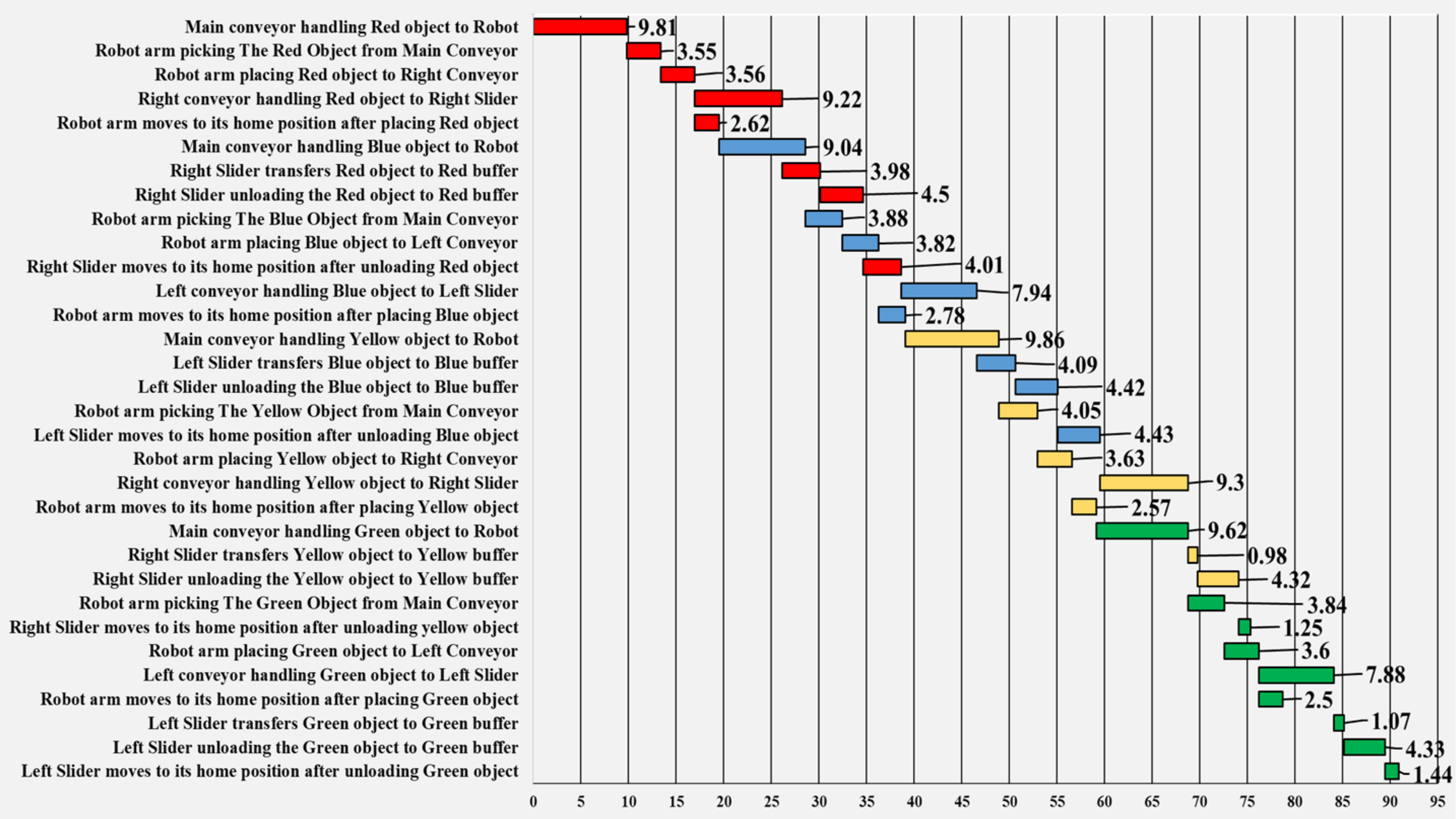


Figure 4.7: Overall time study report

Table 4.7: Detailed time result of the tasks

Task No.	Task Description	Start Time	End Time	Busy Time
1	Main conveyor handling Red object to Robot	0	9.81	**9.81**
2	Robot arm picking The Red Object from Main Conveyor	9.81	13.36	**3.55**
3	Robot arm placing Red object to Right Conveyor	13.36	16.92	**3.56**
4	Right conveyor handling Red object to Right Slider	16.92	26.14	**9.22**
5	Robot arm moves to its home position after placing Red object	16.92	19.54	**2.62**
6	Main conveyor handling Blue object to Robot	19.54	28.58	**9.04**
7	Right Slider transfers Red object to Red buffer	26.14	30.12	**3.98**
8	Right Slider unloading the Red object to Red buffer	30.12	34.62	**4.5**
9	Robot arm picking The Blue Object from Main Conveyor	28.58	32.46	**3.88**
10	Robot arm placing Blue object to Left Conveyor	32.46	36.28	**3.82**
11	Right Slider moves to its home position after unloading Red object	34.62	38.63	**4.01**
12	Left conveyor handling Blue object to Left Slider	38.63	46.57	**7.94**
13	Robot arm moves to its home position after placing Blue object	36.28	39.06	**2.78**
14	Main conveyor handling Yellow object to Robot	39.06	48.92	**9.86**
15	Left Slider transfers Blue object to Blue buffer	46.57	50.66	**4.09**
16	Left Slider unloading the Blue object to Blue buffer	50.66	55.08	**4.42**
17	Robot arm picking The Yellow Object from Main Conveyor	48.92	52.97	**4.05**
18	Left Slider moves to its home position after unloading Blue object	55.08	59.51	**4.43**
19	Robot arm placing Yellow object to Right Conveyor	52.97	56.6	**3.63**
20	Right conveyor handling Yellow object to Right Slider	59.51	68.81	**9.3**
21	Robot arm moves to its home position after placing Yellow object	56.6	59.17	**2.57**
22	Main conveyor handling Green object to Robot	59.17	68.79	**9.62**
23	Right Slider transfers Yellow object to Yellow buffer	68.81	69.79	**0.98**
24	Right Slider unloading the Yellow object to Yellow buffer	69.79	74.11	**4.32**
25	Robot arm picking The Green Object from Main Conveyor	68.79	72.63	**3.84**
26	Right Slider moves to its home position after unloading yellow object	74.11	75.36	**1.25**
27	Robot arm placing Green object to Left Conveyor	72.63	76.23	**3.6**
28	Left conveyor handling Green object to Left Slider	76.23	84.11	**7.88**
29	Robot arm moves to its home position after placing Green object	76.23	78.73	**2.5**
30	Left Slider transfers Green object to Green buffer	84.11	85.18	**1.07**
31	Left Slider unloading the Green object to Green buffer	85.18	89.51	**4.33**
32	Left Slider moves to its home position after unloading Green object	89.51	90.95	**1.44**

Table 4.8: Task dependencies of the system

Task No.	Task Description	Predecessor Task	Related Resources
1	Main conveyor handling Red object to Robot	1	Main Conv.
2	Robot arm picking The Red Object from Main Conveyor	2	Robot Arm
3	Robot arm placing Red object to Right Conveyor	3	Robot Arm
4	Right conveyor handling Red object to Right Slider	4	Right Conv.
5	Robot arm moves to its home position after placing Red object	4	Robot Arm
6	Main conveyor handling Blue object to Robot	5	Right Slider
7	Right Slider transfers Red object to Red buffer	6	Right Slider
8	Right Slider unloading the Red object to Red buffer	8	Right Slider
9	Robot arm picking The Blue Object from Main Conveyor	7	Main Conv.
10	Robot arm placing Blue object to Left Conveyor	9	Robot Arm
11	Right Slider moves to its home position after unloading Red object	10	Robot Arm
12	Left conveyor handling Blue object to Left Slider	12	Left Conv.
13	Robot arm moves to its home position after placing Blue object	11	Robot Arm
14	Main conveyor handling Yellow object to Robot	13	Left Slider
15	Left Slider transfers Blue object to Blue buffer	14	Left Slider
16	Left Slider unloading the Blue object to Blue buffer	16	Left Slider
17	Robot arm picking The Yellow Object from Main Conveyor	15	Main Conv.
18	Left Slider moves to its home position after unloading Blue object	18	Robot Arm
19	Robot arm placing Yellow object to Right Conveyor	17	Robot Arm
20	Right conveyor handling Yellow object to Right Slider	21	Right Conv.
21	Robot arm moves to its home position after placing Yellow object	19	Robot Arm
22	Main conveyor handling Green object to Robot	20	Right Slider
23	Right Slider transfers Yellow object to Yellow buffer	23	Right Slider
24	Right Slider unloading the Yellow object to Yellow buffer	24	Right Slider
25	Robot arm picking The Green Object from Main Conveyor	22	Main Conv.
26	Right Slider moves to its home position after unloading yellow object	26	Robot Arm
27	Robot arm placing Green object to Left Conveyor	25	Robot Arm
28	Left conveyor handling Green object to Left Slider	27	Left Conv.
29	Robot arm moves to its home position after placing Green object	27	Robot Arm
30	Left Slider transfers Green object to Green buffer	28	Left Slider
31	Left Slider unloading the Green object to Green buffer	29	Left Slider
32	Left Slider moves to its home position after unloading Green object	30	Left Slider

4.3 Utilization rate report to identify the resources with more idle time

Since a part of the objective of the Lean Six Sigma was obtaining the methods to optimize and improve the system, the problems and limitation associated with each resource in the target system were obtained individually and listed in the table 4.10. Utilization rate was chosen to identify the resources with more idle time. Table 4.9 shows the utilization rate for each resource individually. The resources with less utilization rate were highlighted and the problems which caused more idle time in that resources were identified. According to OEE, to calculate the utilization rate, both Busy and Idle time should be added to each other to get the production time and production time divides by Busy time gives the utilization of each resource respectively.

Table 4.9: System utilization report

Resource	Busy Time (s)	Idle Time (s)	Cycle time (s)	Utilization %
Main Conveyor	40.40	30.46	70.86	**57.01**
Left Conveyor	15.82	75.13	90.95	**21.05**
Right Conveyor	18.52	72.44	90.96	**20.36**
Robot Arm	34.34	50.55	80.89	**42.45**
Left Slider	19.04	71.17	90.21	**21.10**
Right Slider	19.78	71.91	91.69	**21.57**

Figure. 4.7 shows that the entire scenario takes 90.95 second which is the area under the Gantt chart. Summation of the Busy time of the tasks in table 4.7 is 151.89 second which is more than the duration for accomplishing the entire process. Table 4.7 and 4.8 are illustrating that most of the tasks are performing simultaneously or at the same time. It can be concluded that if Idle time decreases the possibility to run the tasks simultaneously increases. It is essential to consider that decreasing the Idle time without decreasing the Busy times is not possible. Thus, to optimize the idle times by considering the busy time control architecture in slave agents should be modified. For instance, if the robot busy time decreases the idle time of the conveyor to load the next object will decrease consequently. By taking a proper action to modify hardware, software (control software in agents) and layout design of the system, the overall Idle time could be optimized, and the system performance will be enhanced consequently. Table. 4.10 shows the summary of the detected issues and possible solutions to get better timing with utilizing time study technique.

Table 4.10: Detected problems and limitations and proposed solutions

Resource	**Detected problems and limitation**	**Reason**	**Solution**
Main Conveyor	Different busy time for moving the objects	Detection range of the motion sensors	Modification of the detection range (Range for sensor 1, 2 and 3 on slave agent 1)
	Different idle time before moving the objects	Detection range of the Color sensor	Modification of light intensity detection range (Range for sensor 4 on slave agent 6)
		Robot performance dependency	Optimizing the speed of the robot motion by modifying the agent software on slave agent 6
			Modifying the layout design to decrease the distance between the sensors on main conveyor
Robot Arm	The different busy time for robot to move the blue part	Detection range of the Color sensor	Modification of light intensity detection range (Range for sensor 4 on slave agent 6)
	long idle time before moving the objects	Main Conveyor performance dependency	Optimizing the speed of the conveyor motion by modifying the agent software on slave agent 1
Right Side-Conveyor	Low utilization rate (Long Idle time low busy time)	Main Conveyor and Robot arm and right slider performance dependency	Improving the performance of main conveyor, robot and right slider by modifying the agent software on slave agent 1,2 and 4
			Improving the communication between main conveyor, robot and right slider by modifying the interaction protocols in agent software on slave agent 1,2 and 4 and master agent
			Modifying the layout design to optimize the place of exit point on right side-conveyor
	Different busy time in comparison with left side-conveyor	different length of the conveyor	Modifying the length of the conveyor or increasing the speed of conveyor motion by modifying the Slave agent 2
Right Slider	Low utilization rate (Long Idle time low busy time)	Main Conveyor and Robot arm and right Side-conveyor performance dependency	Improving the performance of main conveyor, robot and right slider by modifying the agent software on slave agent 1,2 and 4
			Improving the communication between main conveyor, robot and right slider by modifying the interaction protocols in agent software on slave agent 1,2 and 4 and master agent
			Modifying the layout design to optimize the place of exit point on right side-conveyor
	Different Idle times	Different distance between home position and buffers	Modifying the layout design to change the buffers place to be near to each other

4.4 Simulation result of the system by Arena

To generate an accurate model by Arena and achieving similar behavior as it was in the real system, busy time was considered as the target. Obtaining busy time for each resource and associated task/s, the required velocity of the resources and distance between them for every section of the real system. For this reason, five participants with proper knowledge of the system and its functionality were contributed to measure and collect all the required data with high accuracy and precision instrumentations.

The velocity of objects and resources has been measured with a motion sensor. In this method, an electrostatic transducer in the face of the Motion Sensor transmits a burst of 16 ultrasonic pulses with a frequency of about 49 kHz. The sensor measures the time between the trigger rising edge and the echo rising edge to measure the velocity. The distance between the resources and the displacement of the objects has been measured with a laser distance meter to get the most accurate results. Each participant did the measurement individually and have been asked to calculate the time with considering the velocity and measured distance (Table. 4.11).

As the next step to creating an accurate simulation model, the novel agent-based control architecture with master-slave mechanism should be modeled. Figure 3.11 shows the complete simulation model control architecture in chapter 3. To achieve the most similar behavior of the real system by a simulation model, it was mandatory to consider every hardware, software, and layout design specification in the model as they were in the real system. For this reason, same as the real system, the model divided into same districts which were the entrance of the system and the point which parts were loading to the system, main conveyor, Right and Left Conveyor, Right and Left Slider units and Robotic arm.

Table 4.11: Measured distance and speed by participants

From	To	Among	Resource	Distance (free Unit)	Speed (Distance unit per Second)
Entrance / Sensor 1	Sensor 2	Main Conv.	Main Conv.	53	9.3
Sensor 2	Sensor 3&4	Main Conv.	Main Conv.	12	3.35
Sensor 3&4	Sensor 5	Main Conv. And Right Conv.	Robot Arm	34	12.9
Sensor 3&4	Sensor 6	Main Conv. And Left Conv.	Robot Arm	29	10.4
Sensor 5	Sensor 7 / Right Slider Entrance	Right Conv. and Right Slider	Right Conv.	85	9
Sensor 7 / Right Slider Entrance	Red Buffer	Right Slider	Right Slider	8	8
Sensor 7 / Right Slider Entrance	Yellow Buffer	Right Slider	Right Slider	39	10
Sensor 8 / Left Slider Entrance	Green Buffer	Left Slider	Left Slider	7	8
Sensor 8 / Left Slider Entrance	Blue Buffer	Left Slider	Left Slider	39	10
Sensor 6	Sensor 8 / Left Slider Entrance	Left Conv. and Left Slider	Left Conv.	75	9
Right Slider	Red Buffer	Right Slider and Red Buffer	Right Slider	1	2
Right Slider	Yellow Buffer	Right Slider and Yellow Buffer	Right Slider	1	3.13
Left Slider	Blue Buffer	Left Slider and Blue Buffer	Left Slider	1	3.13
Left Slider	Green Buffer	Left Slider and Green Buffer	Left Slider	1	2.39

To create the simulation model in the Arena, the exact properties of the real system were needed. With measuring the distances between the resources and velocity of the motions same as the real system and utilized them in the model, the time as the result of the simulation was completely match with the time study result of the real system. This simulation model was accurate enough to be modified about the proposed solution in table 4.10 and evaluate their effects on the system. An accurate average of the participant's measurements was utilized in the simulation model and the results were nearly the same as the result of the time study of the real system. This result is shown in Table. 4.12. In addition, visualization in Arena simulation provided graphical representation and animation which gave a better understanding of the behavior of the model. This visualization helped to get an overview of the effects of the system modifications by proposed solutions (Figure 4.9).

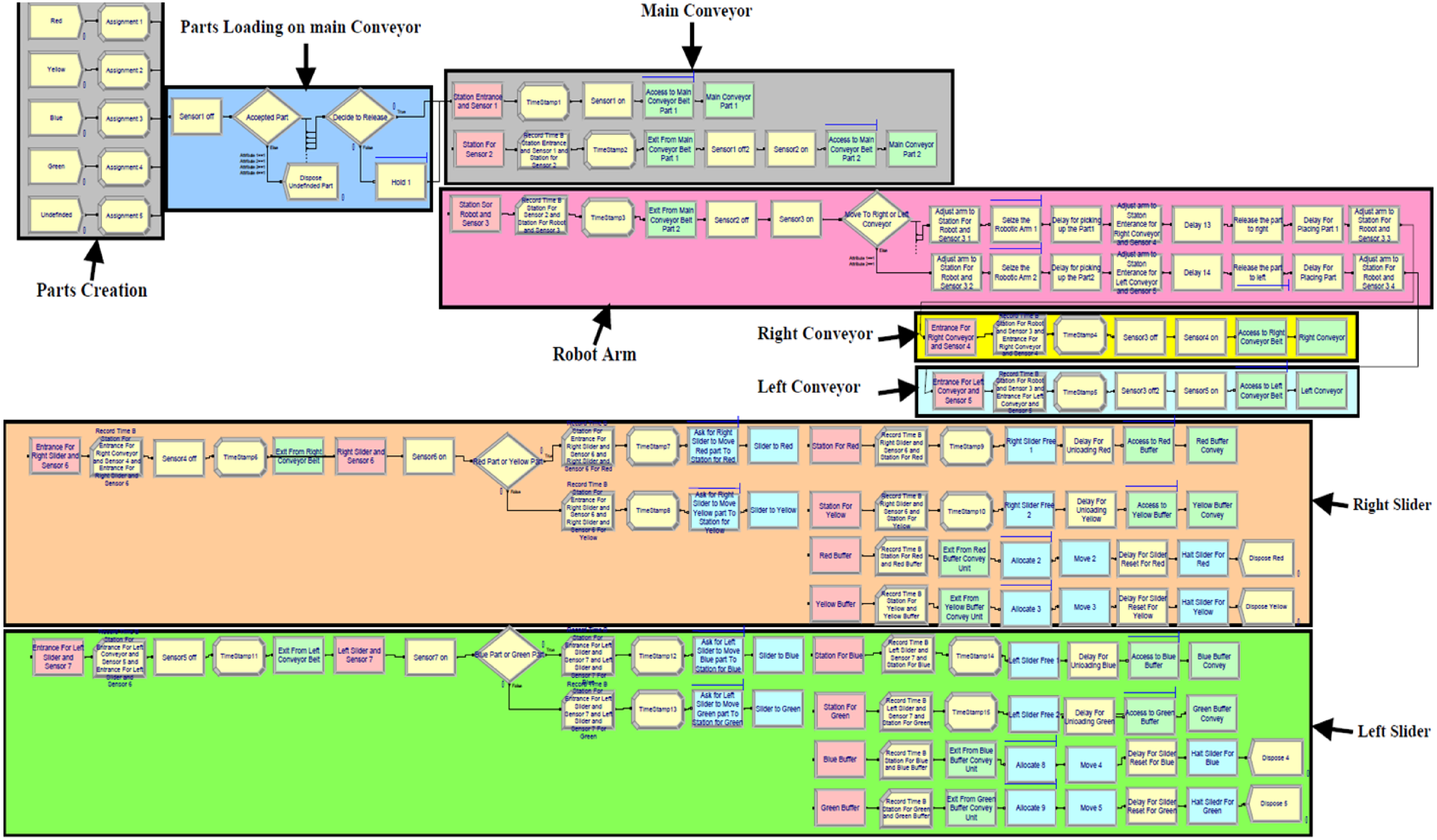


Figure 4.8: Arena simulation model

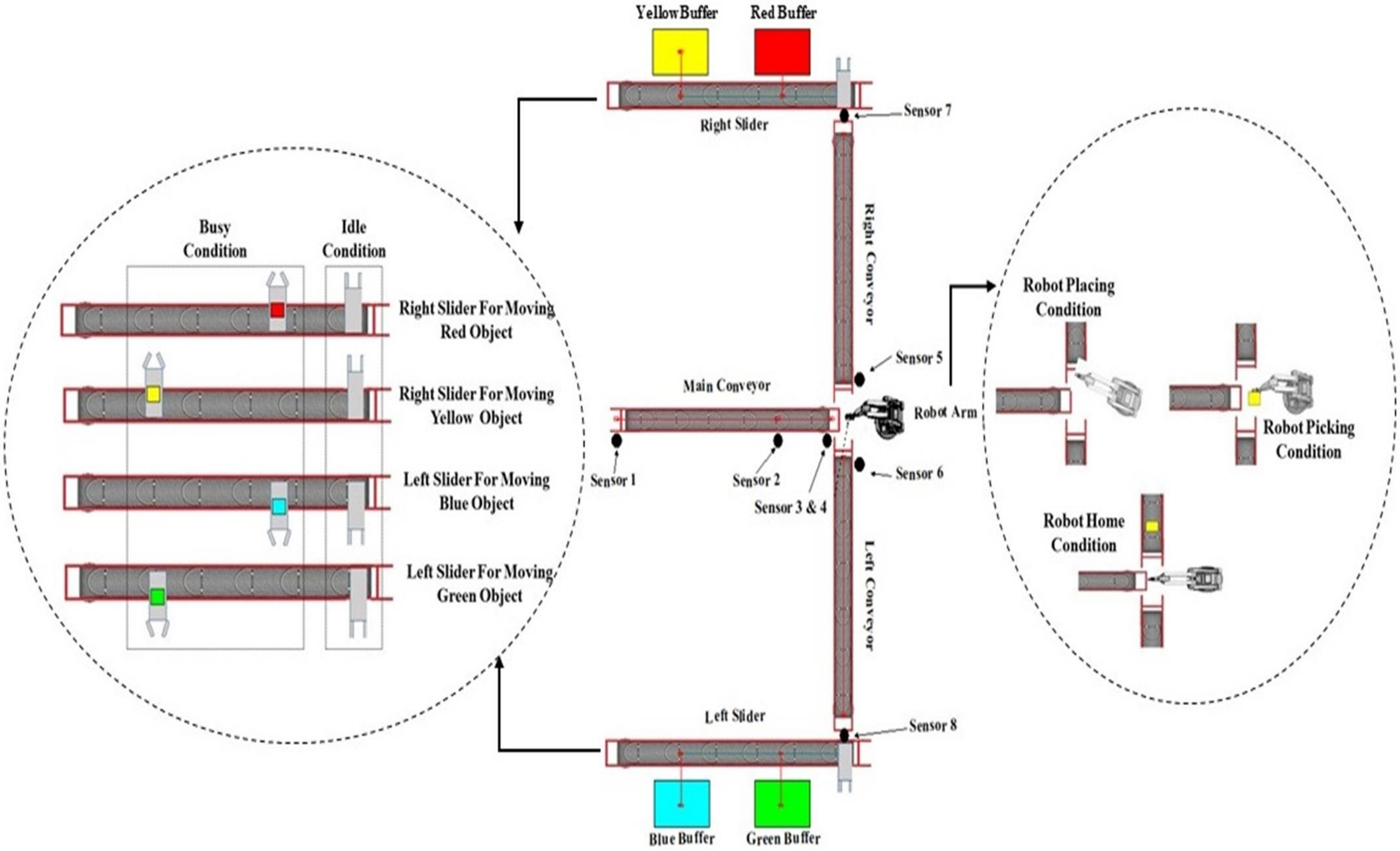


Figure 4.9: Arena visualization of the system

Table 4.12 shows the absolute time difference of 0.5 seconds between busy time in the simulation model and in the real system (Figure 4.10). So that the simulation model verifies and validate the functional specifications and it is reliable to apply any modification and changes.

Table 4.12: Time difference between the real system and Simulation model Busy times

		Busy Time (s)		
Task No.	**Task Description**	**Real System**	**Average of simulation result using Participants observation**	**Absolut Deference**
1	Main conveyor handling Red object to Robot	9.81	9.50	0.31
2	Robot arm picking The Red Object from Main Conveyor	3.55	3.84	0.29
3	Robot arm placing Red object to Right Conveyor	3.56	3.66	0.10
4	Right conveyor handling Red object to Right Slider	9.22	9.40	0.18
5	Robot arm moves to its home position after placing Red object	2.62	2.50	0.12
6	Main conveyor handling Blue object to Robot	9.04	9.50	0.46
7	Right Slider transfers Red object to Red buffer	3.98	3.90	0.08
8	Right Slider unloading the Red object to Red buffer	4.5	4.50	0.00
9	Robot arm picking The Blue Object from Main Conveyor	3.88	3.55	0.33
10	Robot arm placing Blue object to Left Conveyor	3.82	3.66	0.16
11	Right Slider moves to its home position after unloading Red object	4.01	4.08	0.07
12	Left conveyor handling Blue object to Left Slider	7.94	8.33	0.39
13	Robot arm moves to its home position after placing Blue object	2.78	2.50	0.28
14	Main conveyor handling Yellow object to Robot	9.86	9.50	0.36
15	Left Slider transfers Blue object to Blue buffer	4.09	4.09	0.00
16	Left Slider unloading the Blue object to Blue buffer	4.42	4.40	0.02
17	Robot arm picking The Yellow Object from Main Conveyor	4.05	3.84	0.21
18	Left Slider moves to its home position after unloading Blue object	4.43	4.43	0.00
19	Robot arm placing Yellow object to Right Conveyor	3.63	3.66	0.03
20	Right conveyor handling Yellow object to Right Slider	9.3	9.40	0.10
21	Robot arm moves to its home position after placing Yellow object	2.57	2.50	0.07
22	Main conveyor handling Green object to Robot	9.62	9.50	0.12
23	Right Slider transfers Yellow object to Yellow buffer	0.98	0.99	0.01
24	Right Slider unloading the Yellow object to Yellow buffer	4.32	4.32	0.00
25	Robot arm picking The Green Object from Main Conveyor	3.84	3.55	0.29
26	Right Slider moves to its home position after unloading yellow object	1.25	1.25	0.00
27	Robot arm placing Green object to Left Conveyor	3.6	3.66	0.06
28	Left conveyor handling Green object to Left Slider	7.88	8.33	0.45
29	Robot arm moves to its home position after placing Green object	2.5	2.50	0.00
30	Left Slider transfers Green object to Green buffer	1.07	0.71	0.36
31	Left Slider unloading the Green object to Green buffer	4.33	4.32	0.01
32	Left Slider moves to its home position after unloading Green object	1.44	1.44	0.00

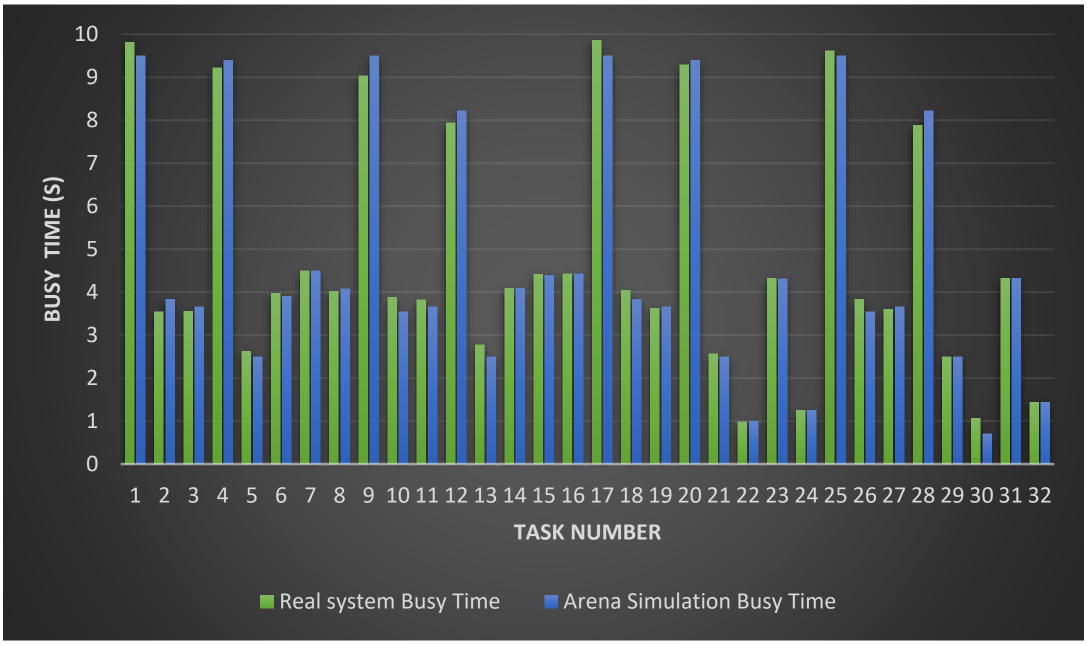


Figure 4.10: Time difference between the real system and Simulation model busy time

4.5 OEE analysis before optimization

After the design and implementation of the proposed agent-based control architecture on the target material handling system and performing a comprehensive time study, the outcome was analyzed to get the overall system performance. For this reason, the OEE standard was considered and utilized to reach this goal. Table 4.1 to 4.6 were utilized to obtain the partial and overall system performance and preparing Table 4.13 consequently.

Table 4.13: Overall and partial system performance based on OEE standard before modification

Recourse	**Main Conveyor**	**Left Side-Conveyor**	**Right Side-Conveyor**	**Robot Arm**	**Right Slider for Red**	**Right Slider for Yellow**	**Left Slider for Blue**	**Left Slider for Green**
Cycle time	68.79	84.11	68.81	90.95	38.63	52.33	84.11	31.44
Down Time	0.33	0.32	0.52	0.40	0.49	0.55	0.94	0.84
Idle time	30.46	68.29	50.29	50.55	26.14	45.77	71.17	24.6
Planned Production Time	38.33	15.82	18.52	40.40	12.49	6.56	12.94	6.84
Run Time	38.00	15.50	18.00	40.00	12.00	6.01	12.00	6.00
Availability %	99.14	97.98	97.19	99.01	96.08	91.62	92.74	87.72
Ideal Cycle Time	8.50	7.00	8.50	9.00	11.00	5.00	11.00	5.00
Total Count	4.00	2.00	2.00	4.00	1.00	1.00	1.00	1.00
Good Count	4.00	2.00	2.00	4.00	1.00	1.00	1.00	1.00
Performance %	89.47	90.32	94.44	90.00	91.67	83.19	91.67	83.33
Quality%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
OEE %	88.70	88.50	91.79	89.11	88.07	76.22	85.01	73.10

OEE percentages are calculated for each part of the system individually (each resource). This percentage provides an accurate overview of the resource’s effectiveness. This percentage makes it easy to identify and track the resources with low performance and evaluate their performance after any modification (solutions) (Figure 4.11).

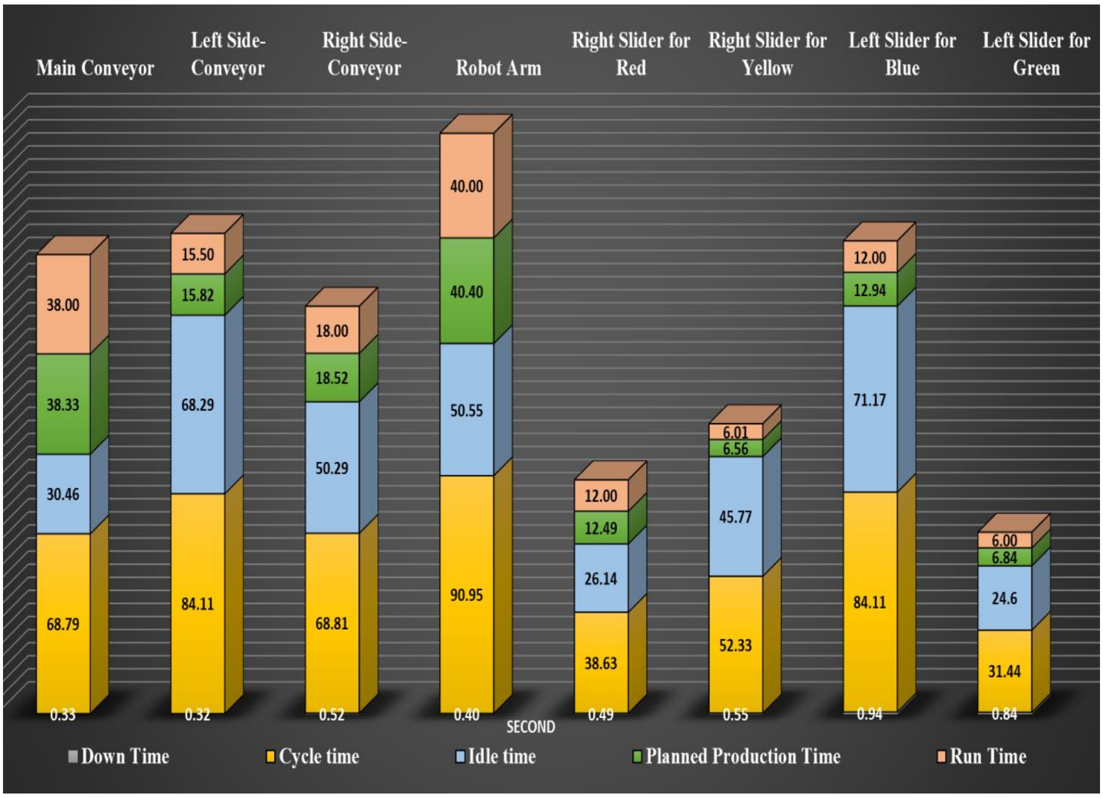


Figure 4.11: Overview of resource time for OEE calculation

Availability of the resources is the first factor which completely depending on resource down time, idle time, and planned production time. Figure 4.12 shows the availability of all the resources is above 90 %, except left Slider for sliding Green object. It means the overall downtime and breakdowns in this resource was not sufficient in comparison with other resources. The main conveyor has 2.3 seconds downtime, which is the result of inflexibility of the main conveyor for moving objects with a different shape. In addition, the main conveyor has 30.46s idle time, which is the result of robot performance. The robot has 99% availability because of the total Idle time and downtime of 50.49s out of 90.95s which is the minimum value in the comparison between the other resources. In availability percentage analysis, the functionality of the slider divided into separated tasks. The reason for this differentiation is the different behavior of sliders to move the objects to the buffers with different distances. Overall availability percentage of sliders is less than the other resources and the reason for this difference is the instability of the Slider's tray in slider units while they are performing and their speed of motion. In addition, sliders are the last resources in the system, and they have a high amount of observed idle time.

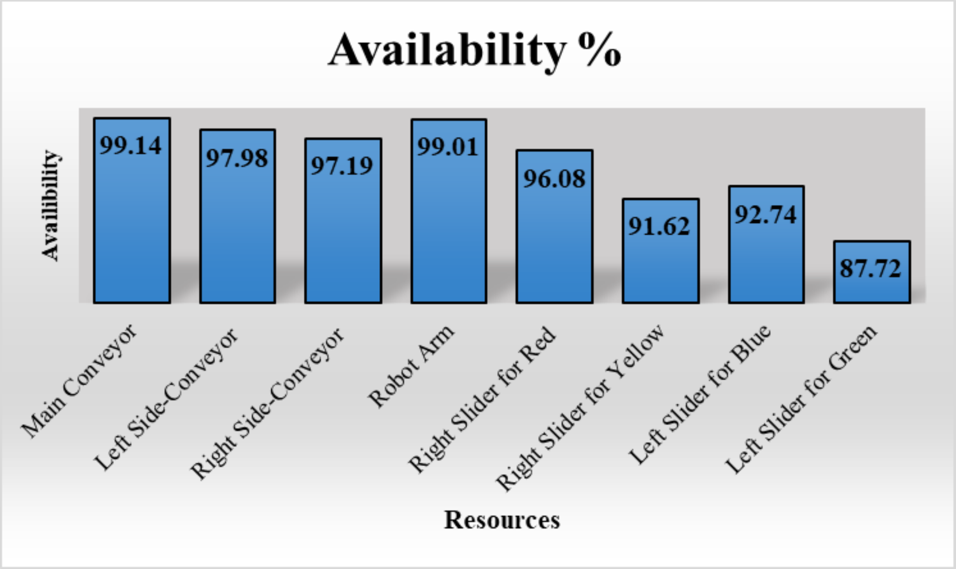


Figure 4.12: Availability percentage of the resources

Figure 4.13 illustrates the performance percentage of the available resources in the system. As it is mentioned in chapter 1, the performance of the resource is a ratio of ideal cycle time and run time for a certain number of products. If the performance percentage approaching to maximum, it shows the resource has less run time and more Ideal cycle time and performing as fast as possible.

The performance of sliders for moving the yellow and green objects (moving the objects to the buffer close to the slider home position) is nearly the same and it is 83.19% and 83.33% respectively. Sliders for moving the Red and Blue objects have the same performance of 91.67%. Left and right side-conveyors performance percentage are different due to the unexpected length inequality (right conveyor 10 cm longer than the left one). The performance of right side-conveyor is 94.44% while the performance percentage in the left one is 90.32%. The result shows that although the right conveyor is longer, it has higher performance. This difference shows that the right conveyor performance is higher due to the better speed to move the objects and less downtime with a longer length. In addition, the performance of the side conveyors is totally depending on the Ideal Cycle time, Run Time and total good counted products. Total good counted products and Ideal cycle time for both conveyors are considered the same. So that the only reason for the mentioned issue should be Run Time. Run time is affecting by the Idle time and downtime, which both have less value in Right conveyor significantly. It is noteworthy that Idle and downtimes are affecting by the other resources in addition to the conveyors itself. It means, although the right conveyor is 10 cm longer than the Left one, the proper value of run time and down time compensates this difference and gives a better performance as the result.

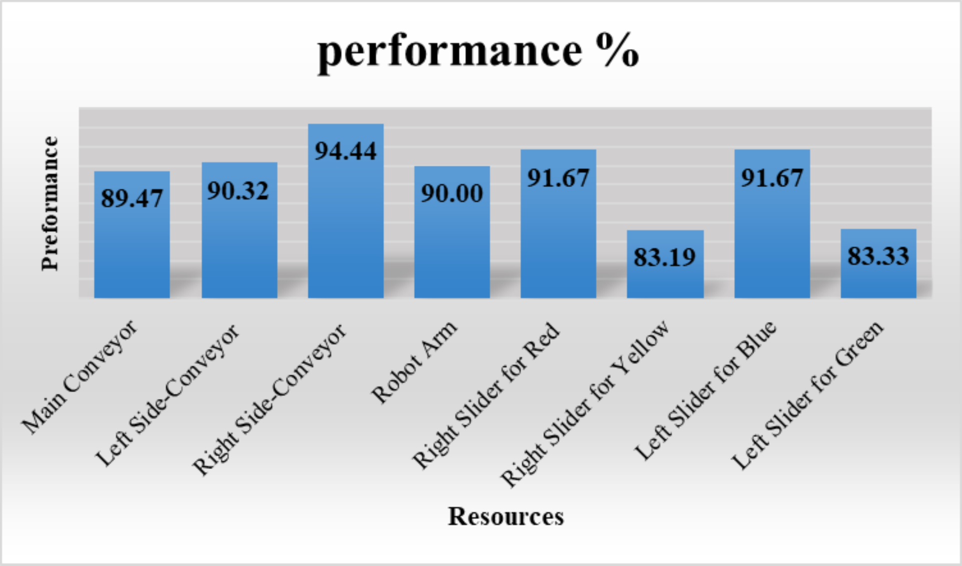


Figure 4.13: Performance percentage of the resources

As mentioned in chapter 1, the OEE percentage of the resources is depending on availability, performance, and quality. The main task in the target system was product distribution and all of the loaded objects into the system were assumed as products with good quality and the quality percentage for entire resources in the system considered as 100%. Figure 4.14 shows the OEE percentage of the resources individually. The effect of the detected problems and limitations in table 4.10 is detectable on OEE percentage for each resource. OEE is affecting by availability and performance, and its percentage validates all of the identified problem and limitations. It means for improving and optimizing the system, OEE evaluation is an appropriate standard besides Time study.

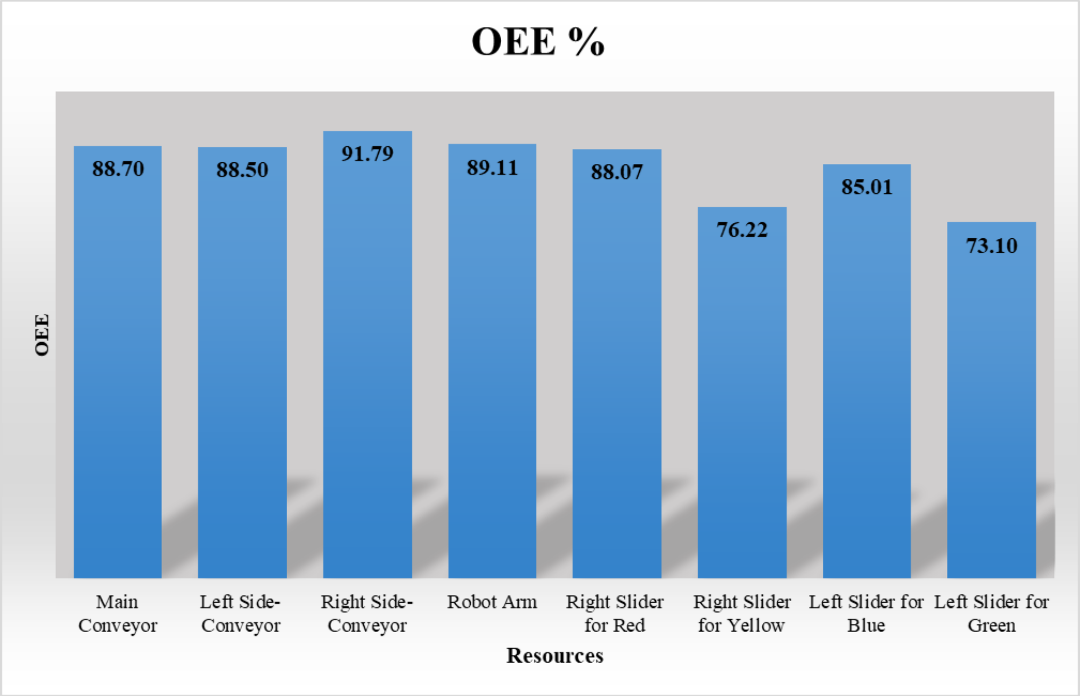


Figure 4.14: OEE percentage of the resources

4.6 OEE analysis after optimization

Any modification on the system aiming to solve the identified problems and limitation of the target system has a different influence on the OEE percentage. In order to identify the solutions which, effect more on OEE percentage and increasing the performance of the system, a function has been developed. The function includes factors which have a direct relationship with the proposed agent-based architecture. In order to optimize these factors, the software agent in slaves or in the master agent should be modified. Based on the identified problems and associated solutions presented in 4.10, speed of motion and distance have been selected as the target factors. Modifying the distance between the resources or speed of motions requires a comprehensive consideration of the system capabilities to adapt itself with this change. Furthermore, if the proposed agent-based control architecture is properly modifiable, then there is the possibility to apply the proposed solutions.

In this research, the distance between the resources changed to $1/2$ and $2/3$ of the distance in the real system; Also the speed changed to the maximum level with considering the required modifications for software agents in slaves and interaction protocols in master agent. For this reason, the factors which can be modified to improve the performance of the system are formed as a parameter vector (Equation 4.1).

$$p = [p_1, p_2, p_3] \qquad \text{(Equation 4.1)}$$

Here, p_2 is the distance between the resources or segments (stations) and p_3 is the speed of motion of the resources. p_1 is the cycle time, including Idle and Busy times (Equation 4.2).

$$T_i, T_b \in p_1 \qquad \text{(Equation 4.2)}$$

Here, T_i is the idle Time and T_b is the busy time. Cycle time is influencing by the velocity and distance between the considered resources; So that to reach to minimum p_1 we have the following:

$$p_1 = \frac{p_2}{p_3} \qquad \text{(Equation 4.3)}$$

$$p_{1,\min} = \frac{p_{2,\min}}{p_{3,\mathrm{m}ax}} \qquad \text{(Equation 4.4)}$$

As it showed in the time study result of the resources, in most cases, decreasing the duration of the tasks (Busy Time) the system resource Idle times will be decreased consequently. In addition, Idle time in a resource is affecting by the performance of the other relative resources. As the time study and OEE result showed, each resource performance was affecting by idle and busy times in a unique manner. C_1 considered as effectiveness coefficient of idle time and it shows that in different systems idle time has different effects. C_2 considered as effectiveness coefficient of busy time, which will be evaluated internally for each resource and rarely will be affected by other parameters which are not related to resources itself (Equation 4.5).

$$p_1 = \sum C_1 T_i + C_2 T_b \qquad \text{(Equation 4.5)}$$

The proposed solutions to improve the performance of the system in this study are focused on Time, velocity and distance as an effective factor of the system. These parameters effecting on idle and busy time simultaneously. However, the influence of the changes on busy time in a resource is going to be considered as a change in idle time in another resource. So that to investigate the influence of each of the proposed solutions, C_1 assumed as 0 to investigate the effects of focusing on busy time (Equation 4.6).

$$C_1 = 0 \rightarrow p_1 = \sum C_2 T_b \quad \text{(Equation 4.6)}$$

Thus, to reach to minimum p_1, p_2 (Distance) should be minimized and p_3 (Velocity) should be maximized.

Follow the instruction above and to evaluate the solution, the velocity of the resources has been modified to the maximum possible value in the Arena simulation model. Increasing the velocity is based on the real resource's capacity and properties and also its influence on the related resources before and after. For instance, the velocity of the conveyors increased to the point that the conveyor can handle the objects accurately with less vibration during the transportation and with considering the required time for the robot to finish pick and place task. For this reason, without changing the system layout, several tests are done on the conveyor to get the maximum velocity value. The effects of the distance between the resources were investigated by changing the length of conveyors in the simulation model without changing the speed of motion for resources. Table 4.14 shows the result of the modified simulation model to investigate the effect of the solutions on resources busy times. In addition, a comprehensive comparison between the time before and after implementing the solutions on the simulation model has been visualized in Figure 4.15.

Table 4.14: Task duration on the real system and after modification on the simulation model

Task Description	Real	Average of Simulation results	2/3 of the real Distance Change	1/2 of the real Distance Change	Speed Limit Change to Maximum
Main conveyor handling Red object to Robot	9.81	9.50	6.63	5.32	8.20
Robot arm picking The Red Object from Main Conveyor	3.55	3.84	3.84	3.84	3.25
Robot arm placing Red object to Right Conveyor	3.56	3.66	3.66	3.66	3.20
Right conveyor handling Red object to Right Slider	9.22	9.40	5.60	4.47	8.80
Robot arm moves to its home position after placing Red object	2.62	2.50	2.50	2.50	1.99
Main conveyor handling Blue object to Robot	9.04	9.50	6.63	5.32	8.20
Right Slider transfers Red object to Red buffer	3.98	3.90	2.64	2.03	3.70
Right Slider unloading the Red object to Red buffer	4.50	4.50	4.50	4.50	4.24
Robot arm picking The Blue Object from Main Conveyor	3.88	3.55	3.55	3.55	3.34
Robot arm placing Blue object to Left Conveyor	3.82	3.66	3.66	3.66	3.30
Right Slider moves to its home position after unloading Red object	4.02	4.08	2.68	2.06	3.90
Left conveyor handling Blue object to Left Slider	7.94	8.33	5.68	4.47	7.50
Robot arm moves to its home position after placing Blue object	2.78	2.50	2.50	2.50	1.99
Main conveyor handling Yellow object to Robot	9.86	9.50	6.63	5.32	8.20
Left Slider transfers Blue object to Blue buffer	4.09	4.09	2.72	2.00	4.02
Left Slider unloading the Blue object to Blue buffer	4.42	4.40	4.40	4.40	4.20
Robot arm picking The Yellow Object from Main Conveyor	4.05	3.84	3.84	3.84	3.25
Left Slider moves to its home position after unloading Blue object	4.43	4.43	2.95	2.27	4.06
Robot arm placing Yellow object to Right Conveyor	3.63	3.66	3.66	3.66	3.20
Right conveyor handling Yellow object to Right Slider	9.30	9.40	5.60	4.47	8.80
Robot arm moves to its home position after placing Yellow object	2.57	2.50	2.50	2.50	1.99
Main conveyor handling Green object to Robot	9.62	9.50	6.63	5.32	8.20
Right Slider transfers Yellow object to Yellow buffer	0.98	0.99	0.62	0.49	0.70
Right Slider unloading the Yellow object to Yellow buffer	4.32	4.32	4.32	4.32	4.10
Robot arm picking The Green Object from Main Conveyor	3.84	3.55	3.55	3.55	3.34
Right Slider moves to its home position after unloading yellow object	1.25	1.25	0.78	1.20	1.00
Robot arm placing Green object to Left Conveyor	3.60	3.66	3.66	3.66	3.30
Left conveyor handling Green object to Left Slider	7.88	8.33	5.68	4.47	7.50
Robot arm moves to its home position after placing Green object	2.50	2.50	2.50	2.50	1.99
Left Slider transfers Green object to Green buffer	1.07	0.71	0.62	0.49	0.66
Left Slider unloading the Green object to Green buffer	4.33	4.32	4.32	4.32	4.10
Left Slider moves to its home position after unloading Green object	1.44	1.44	1.03	0.82	1.07

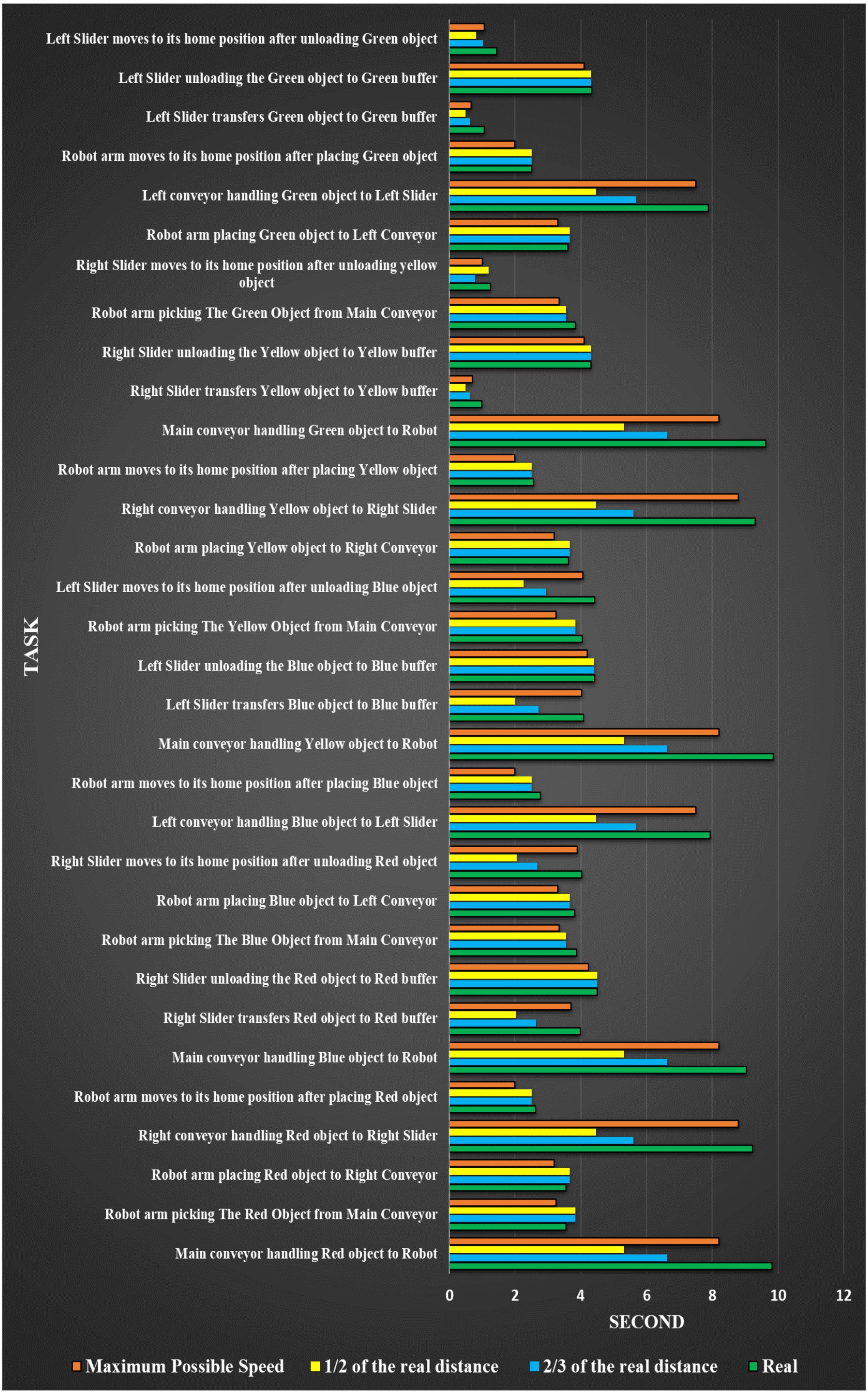


Figure 4.15: Comparison of task duration (busy time) before and after the implementation of solutions

In order to investigate the effect of solutions on OEE percentage, availability, performance and the quality of the system were required. As it has been mentioned before the quality of the objects considered as 100%. And the factors required to obtain the Availability and Performance percentage (Down time, Idle time, Cycle time, Run time and Planed production time) have been obtained for each solution and each resource individually from simulation model (Table 4.15).

Table 4.15: OEE analysis before and after optimization

Recourse	***Cycle Time***	***Down Time***	***Idle time***	***Planned Production Time***	***Run Time***	***Availability %***	***Ideal Cycle Time***	***Total Count***	***Good Count***	***Performance %***	***Quality %***	***OEE %***
Modified to Max Possible Speed												
Main Conveyor	58.36	0.33	25.56	32.80	32.47	98.99	8.00	4.00	4.00	98.55	100.00	97.56
Left Conveyor	72.50	0.32	57.50	15.00	14.68	97.87	7.00	2.00	2.00	95.37	100.00	93.33
Right Conveyor	63.88	0.52	46.28	17.60	17.08	97.05	8.50	2.00	2.00	99.53	100.00	96.59
Robot Arm	66.99	0.40	32.80	34.19	33.79	98.83	8.00	4.00	4.00	94.70	100.00	93.59
Right Sliders for Red	35.29	0.49	23.45	11.84	11.35	95.86	11.00	1.00	1.00	96.92	100.00	92.91
Right Sliders for Yellow	34.39	0.55	28.59	5.80	5.25	90.52	5.00	1.00	1.00	95.24	100.00	86.21
Left Slider for Blue	55.07	0.70	42.79	12.28	11.58	94.30	11.50	1.00	1.00	99.31	100.00	93.65
Left Slider for Green	23.25	0.80	17.42	5.83	5.03	86.28	5.00	1.00	1.00	99.40	100.00	85.76
Modified to 2/3 distance between the resources												
Main Conveyor	56.23	0.33	29.71	26.52	26.19	98.76	6.00	4.00	4.00	91.64	100.00	90.50
Left Conveyor	69.12	0.32	57.76	11.36	11.04	97.18	5.00	2.00	2.00	90.58	100.00	88.03
Right Conveyor	50.90	0.52	39.70	11.20	10.68	95.36	5.00	2.00	2.00	93.63	100.00	89.29
Robot Arm	65.94	0.40	26.52	39.42	39.02	98.99	9.50	4.00	4.00	97.39	100.00	96.40
Right Sliders for Red	29.55	0.49	19.73	9.82	9.33	95.01	9.00	1.00	1.00	96.46	100.00	91.65
Right Sliders for Yellow	27.07	0.55	21.35	5.72	5.17	90.38	5.00	1.00	1.00	96.71	100.00	87.41
Left Slider for Blue	45.30	0.70	35.23	10.07	9.37	93.05	9.00	1.00	1.00	96.05	100.00	89.37
Left Slider for Green	29.79	0.80	23.82	5.97	5.17	86.60	5.00	1.00	1.00	96.71	100.00	83.75
Modified to 1/2 distance between the resources												
Main Conveyor	50.69	0.33	29.41	21.28	20.95	98.45	5.00	4.00	4.00	95.47	100.00	93.98
Left Conveyor	62.37	0.32	53.43	8.94	8.62	96.42	4.00	2.00	2.00	92.81	100.00	89.49
Right Conveyor	43.42	0.52	34.55	8.87	8.35	94.14	4.00	2.00	2.00	95.81	100.00	90.19
Robot Arm	60.40	0.40	21.28	39.12	38.72	98.98	9.00	4.00	4.00	92.98	100.00	92.02
Right Sliders for Red	25.88	0.49	17.29	8.59	8.10	94.30	8.00	1.00	1.00	98.77	100.00	93.13
Right Sliders for Yellow	23.05	0.50	17.54	5.51	5.01	90.93	5.00	1.00	1.00	99.80	100.00	90.74
Left Slider for Blue	39.02	0.65	30.35	8.67	8.02	92.50	8.00	1.00	1.00	99.75	100.00	92.27
Left Slider for Green	28.98	0.60	23.35	5.63	5.03	89.34	5.00	1.00	1.00	99.40	100.00	88.81
Real system without modification												
Main Conveyor	68.79	0.33	30.46	38.33	38.00	99.14	8.50	4.00	4.00	89.47	100.00	88.70
Left Conveyor	84.11	0.32	68.29	15.82	15.50	97.98	7.00	2.00	2.00	90.32	100.00	88.50
Right Conveyor	68.81	0.52	50.29	18.52	18.00	97.19	8.50	2.00	2.00	94.44	100.00	91.79
Robot Arm	78.73	0.40	38.33	40.40	40.00	99.01	9.00	4.00	4.00	90.00	100.00	89.11
Right Sliders for Red	38.63	0.49	26.14	12.49	12.00	96.08	11.00	1.00	1.00	91.67	100.00	88.07
Right Sliders for Yellow	36.73	0.55	30.18	6.55	6.00	91.60	5.00	1.00	1.00	83.33	100.00	76.34
Left Slider for Blue	59.51	0.70	46.57	12.94	12.24	94.59	11.00	1.00	1.00	89.87	100.00	85.01
Left Slider for Green	31.44	0.80	24.6	6.84	6.04	88.30	5.00	1.00	1.00	82.78	100.00	73.10

Figure 4.16 to 4.23 have been provided to obtain the effect of the proposed solution in each resource and choosing the most effective one. This graphical representation helps to investigation the OEE and related factors after implementing the solution. Each figure shows the percentage of Availability, Performance, and OEE respectively.

Analyzing the outcome of the system after modification of the simulation model verify that the OEE percentage has been changed by each solution significantly. However, this change has a direct relationship with system performance and availability. In almost all the resources, all of the solutions increase the performance of the resources but not equally.

It was expected to get better OEE percentage by changing the distance between the resources (decreasing the distances to $\frac{2}{3}$ and $\frac{1}{2}$ of the actual distance in the simulation model). Although these changes improve the OEE percentages for most of the resources which are connected along with a conveyor unit, in some of them the percentage of OEE dropped.

The main conveyor had two different segments (between sensor 1-2 and sensor 2-3) with different speed of motion. Modification of Speed has the highest influence on OEE percentage for this resource. Also, changing the distance between the resources on the main conveyor without modifying the speed, increases the OEE percentage. These changes are 1.8% and 5.28% of improvement for decreasing the distances to $\frac{2}{3}$ and $\frac{1}{2}$ of the actual distance respectively. The maximum effect on OEE percentage is 8.86% belongs to increasing the speed of the main conveyor segments.

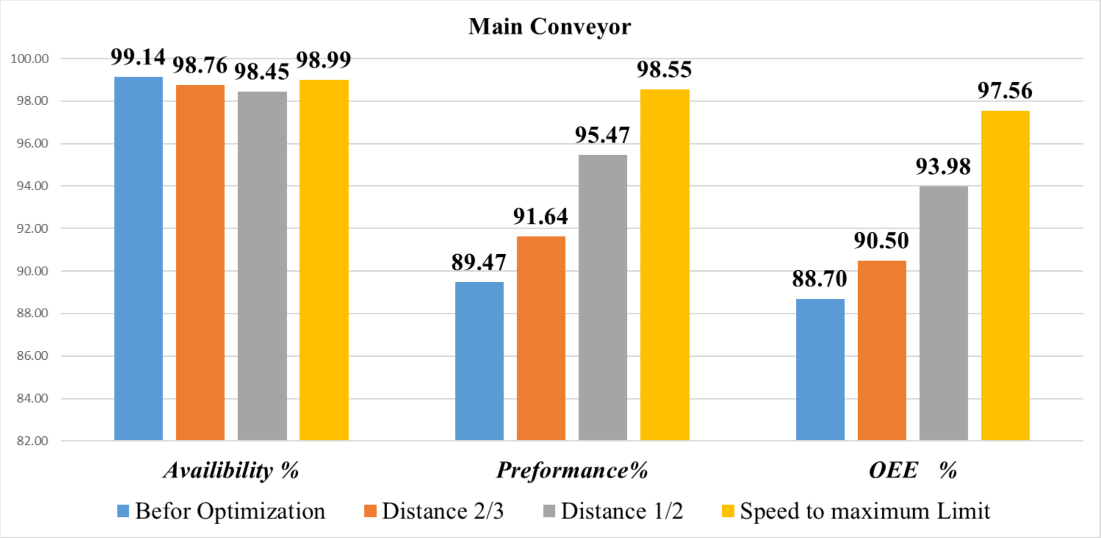


Figure 4.16: Comparison of OEE and associated factors for the main conveyor

Figure 4.16 shows that the performance percentage of the main conveyor for all of the solutions increased significantly. However, the availability of this resource for all of the modifications decreased slightly. The reason for this value drop for availability percentage is its dependency to idle time. In the main conveyor, idle time is completely depending on robot availability percentage which was not changing significantly with applying the solutions. Thus, decreasing the distance decreases the busy time of the main conveyor when the idle time is not changing due to robot dependency. On the other hand, performance percentage after applying the solutions increased because for all cases the run time decreased while the ideal cycle time was constant or decreased slightly.

Figure 4.17 illustrates that the OEE percentage changes similarly for the robot arm with the implementation of the proposed solutions on the simulation model. OEE percentage for this resource is mostly influenced by the performance percentage. The speed of robot motion is the only factor can change the robot OEE percentage, and it is depending on the distance between the point which robot pick the objects and the point to place them. The improved percentages of OEE for the robot are 7.39% and 2.98 % for decreasing the distances to $\frac{2}{3}$ and $\frac{1}{2}$ of the actual distance and 4.70% for modifying the speed of robot motion. The improvement in OEE percentage for decreasing the distance between pick and place points to $\frac{2}{3}$ of the actual distance is more than the improvement for $\frac{1}{2}$ the actual distance. Decreasing the distance between these two points needs a complex robot motion to reach to the parts accurately. Furthermore, a complex robot motion needs more time in comparison with the simple motions.

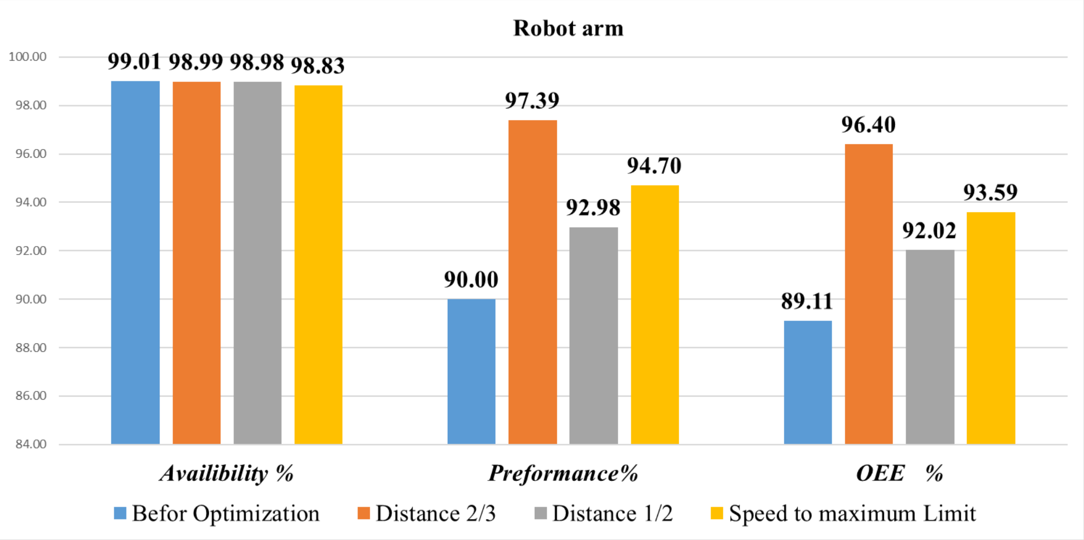


Figure 4.17: Comparison of OEE and associated factors for root arm

Figure 4.18 and 4.19 show that the observed changes in OEE percentage belong to side conveyors are mostly similar. In the right side-conveyor, the OEE percentages are decreased by 2.5% to 1.60% belong to decreasing the distance to $\frac{2}{3}$ and $\frac{1}{2}$ of the actual distance. However, the OEE percentage increased by 4.8% by changing the maximum speed in this resource. The OEE percentage in left conveyor almost remained the same by changing the distance but significantly improved by 4.83 % with modifying the speed to maximum.

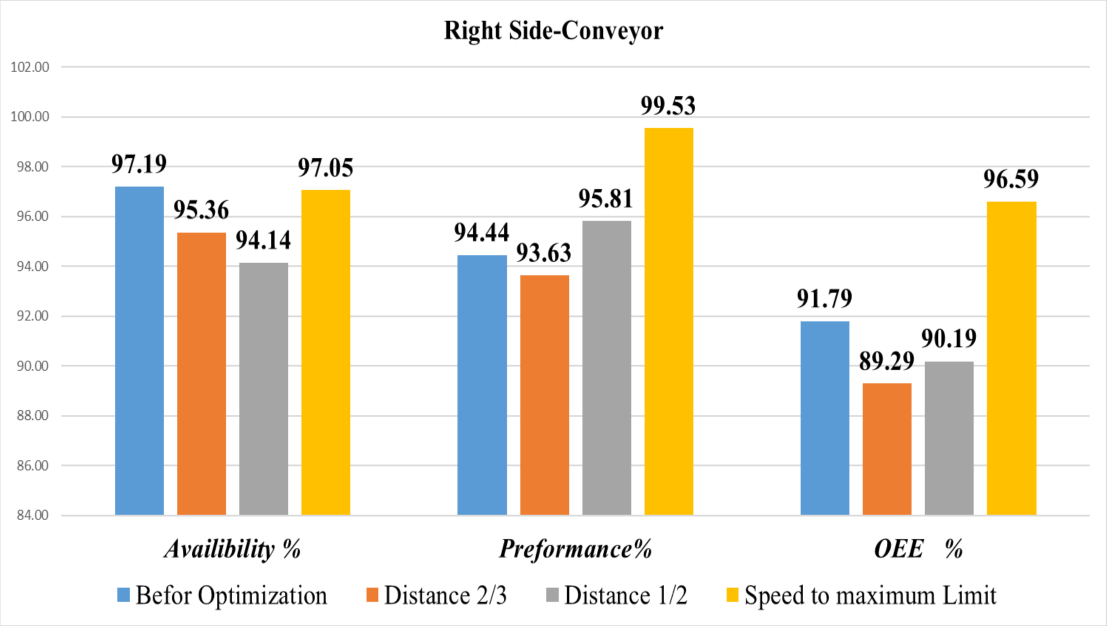


Figure 4.18: Comparison of OEE and associated factors for Right Side-Conveyor

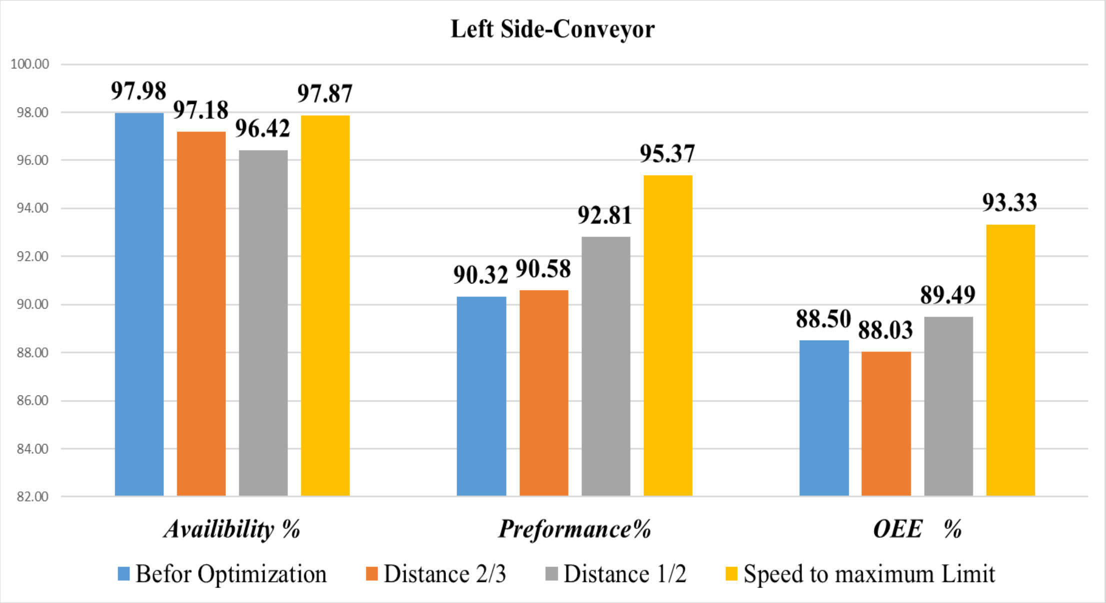


Figure 4.19: Comparison of OEE and associated factors for Left side-conveyor

Figure 4.18 and 4.19 show that the availability of the side-conveyors decreased by modification of the distances for both conveyors. Furthermore, side-conveyor availability percentage is depending on robot arm performance. It means decreasing the distance for side conveyors decreases the busy time for this resource, but the idle time is completely depending on robot performance. As figure 4.17 shows, the robot arm

has better performance percentage when the distance decreases to $^{2}/_{3}$ the actual distance. Thus, the side-conveyors availability for decreasing the distance $^{2}/_{3}$ is more than $^{1}/_{2}$. However, the ideal cycle time for side-conveyors significantly decreases and result in a better performance after modifying the distances.

Sliders have totally different behaviors about the effectiveness of solutions. The percentage of OEE improves by changing the distance of the segments. Right and left sliders behave differently about the effectiveness of solutions for moving the part to the buffers near to the slider home position and the buffer far from home position.

Figure 4.20 shows that in right slider, the OEE percentage belongs to short-range transfer (Red and Blue Objects) improves between 3.58% to 4.43% which are the value as the result of changing the distances to $^{2}/_{3}$ and ½ of the actual distance. On the other hand, OEE percentage improvement for Left slider for a short range of motion and it is between 4.36% to 7.26% for changing the distances to $^{2}/_{3}$ and ½ of the actual distance.

Furthermore, the influence of the speed on OEE percentage for both slider in the short range of motion is significant. Increasing the speed of motion to the maximum limit, influences on OEE percentage significantly which is 4.84% for the right slider and

8.64% for the left one. Although, the availability of the sliders for short range of motion decreased slightly due to the dependency of these resources to the performance of main and side conveyors and robot arm, but the performance percentage increased significantly due to decreasing the run time for all of the modifications.

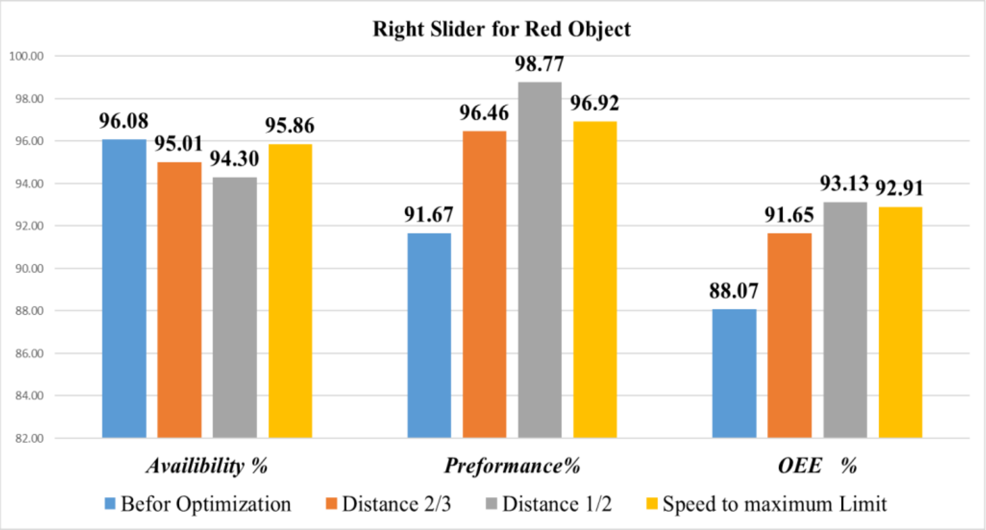


Figure 4.20: Comparison of OEE and associated factors for Right slider (Red Object)

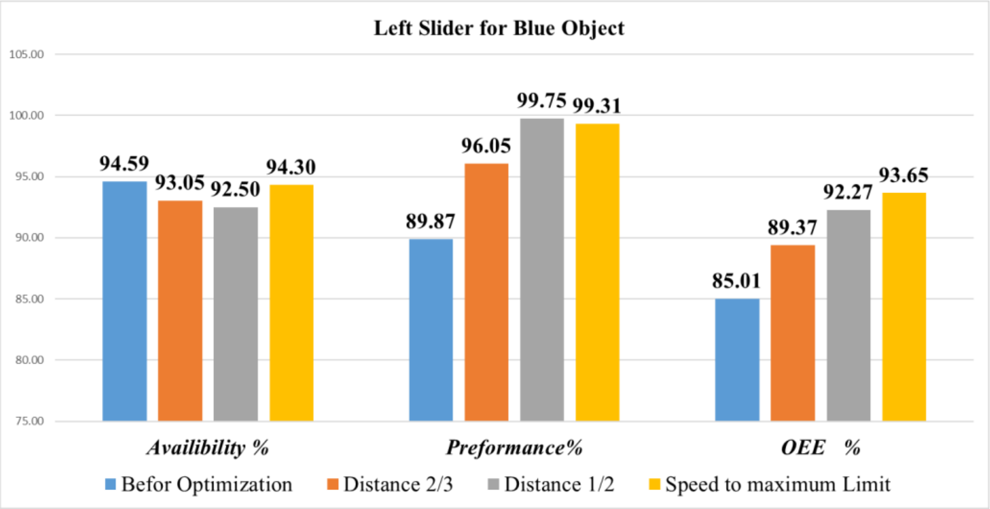


Figure 4.21: Comparison of OEE and associated factors for Left slider (Blue Object)

Figure 4.22 and 4.23 show that the sliders behaving differently for the long range of motion (Yellow and Green Objects). Unlike the short range of motion, the OEE percentage of sliders increased more by modifying the distance. Furthermore, the availability percentage in both slider for the long range of motion remained nearly the same for all of the modifications.

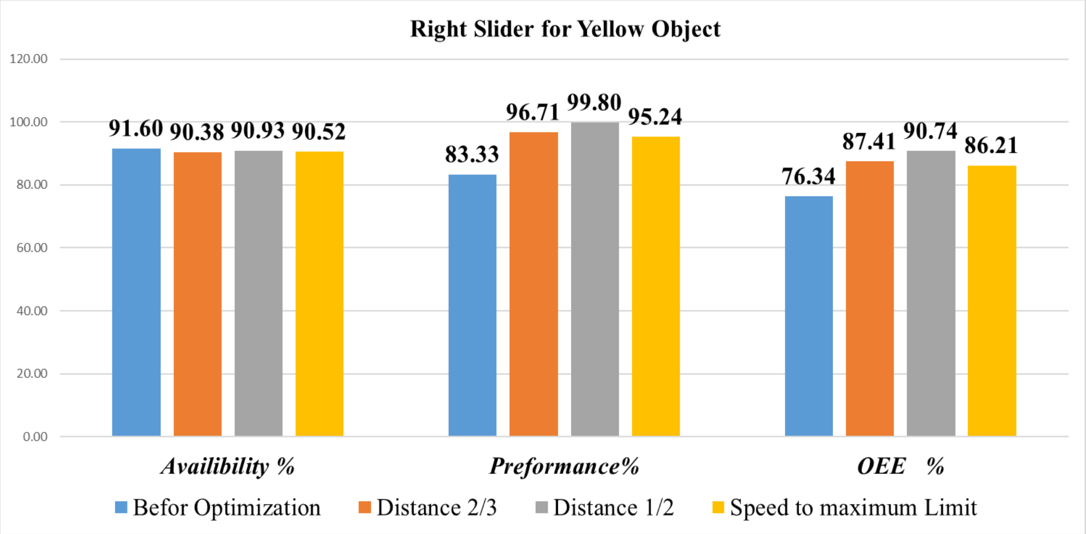


Figure 4.22: Comparison of OEE and associated factors for Right slider (Yellow Object)

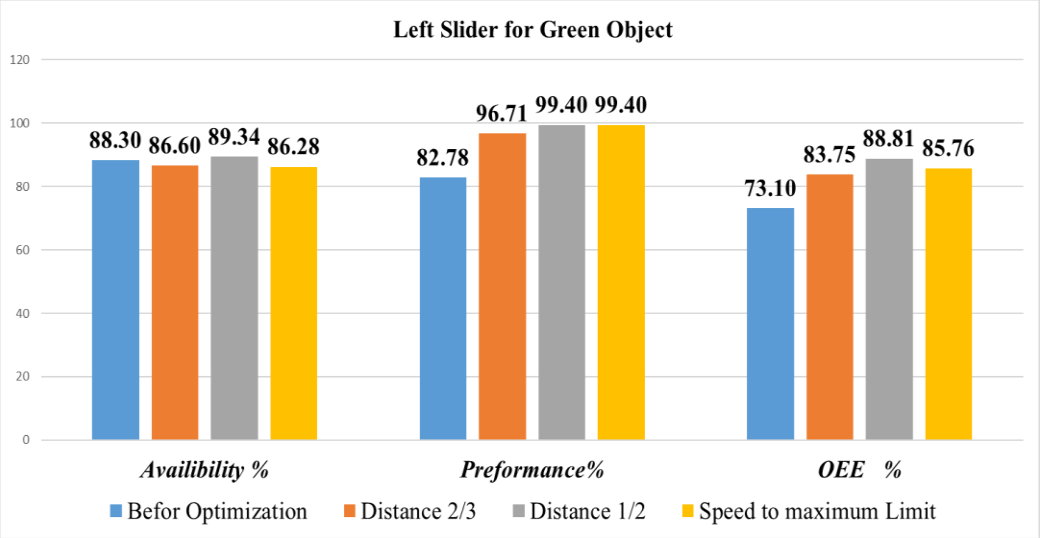


Figure 4.23: Comparison of OEE and associated factors for Right slider (Green Object)

Table 4.16 shows that all of the proposed solutions influence the OEE percentage. In addition, it is essential to consider that the influences on OEE percentages have different value and importance for each resource and associated solution. In order to generalize the solution to select the best optimization factor, each factor a priority has been considered. This Priority is based on the value of improvement of OEE percentage. For instance, for main conveyor we have p_3 (First) $p_{2\text{-}1}$(Second), $p_{2\text{-}2}$ (Third) which means the first factor has the highest influence on OEE was speed and the second and third priorities are for decreasing the distance to ½ and $^2/_3$ respectively.

Table 4.16: OEE improvement percentage for each resource

	OEE Improvement %			**Priority of the effectiveness**		
Resource	**½ of the actual distance ($p_{2\text{-}1}$)**	**$^2/_3$ of the actual distance ($p_{2\text{-}2}$)**	**Speed to max limit (p_3)**	**First**	**Second**	**Third**
Main Conv.	**5.28**	**1.80**	**8.86**	p_3	$p_{2\text{-}1}$	$p_{2\text{-}2}$
Right side-Conv.	**- 1.60**	**- 2.50**	**4.80**	p_3	***	***
Left Side-Conv.	**0.99**	**- 0.47**	**4.83**	p_3	$p_{2\text{-}1}$	***
Robot arm	**2.91**	**7.29**	**4.48**	$p_{2\text{-}2}$	p_3	$p_{2\text{-}1}$
Right Slider (short range)	**5.06**	**3.58**	**4.21**	$p_{2\text{-}1}$	p_3	$p_{2\text{-}2}$
Right slider (long range)	**14.40**	**11.07**	**9.87**	$p_{2\text{-}1}$	$p_{2\text{-}2}$	p_3
Left Slider (short range)	**7.26**	**4.36**	**8.64**	p_3	$p_{2\text{-}1}$	$p_{2\text{-}2}$
Left Slider (long range)	**15.71**	**10.56**	**12.66**	$p_{2\text{-}1}$	p_3	$p_{2\text{-}2}$

In general, based on the Table. 4.16, to enhance the performance of the main conveyor increasing the speed to the maximum possible value has the highest impact on OEE percentage. However, decreasing the distance to ½ actual size effect more on OEE percentage in comparison with decreasing the distance to $^2/_3$ actual distance.

Speed of motion is the only factor to improve the percentage of OEE in right side-conveyor. As table 4.16 shows, any modification on distance effected negatively on this resource. Thus, the only solution to improve the OEE percentage for side conveyor is increasing the speed to the maximum possible limit. The mentioned description can be suggested for left side-conveyor with considering that decreasing the distance to ½ actual size increase the OEE percentage less than one percent which is neglectable.

Due to the assigned task and hardware design of the robot arm, decreasing the distance between the points in which the robot is picking and placing the objects, to ⅔ actual size, increases the OEE percentage more than the other factors. Furthermore, increasing the robot speed to maximum has more impact on OEE percentage in comparison with decreasing the distance to ½ actual size.

For slider units, the impact of the target factors will be different for short and long range of motions. As Table 4.16 shows, for both range of motion in the right slider, decreasing the distance to ½ actual size has the highest impact on OEE. However, increasing the speed of motion for short range and decreasing the distance to ⅔ actual size for long range, have the second priory to increase the OEE percentage.

In the left slider unit, increasing the speed of motion for short range has the highest impact of the OEE percentage. Decreasing the distance to ½ and ⅔ actual size have the second and third priority to improve the OEE respectively. This behavior is totally different for the long range of motion in the left slider. Decreasing the distance to ½ actual size has the highest impact on OEE and increasing the speed and decreasing the distance to ⅔ actual size have the second and third priority on improving the OEE percentage.

It is noteworthy that, there is the possibility to implement all of the proposed solutions if the agent software in slaves and master and layout design in the target system being modified properly. However, in this thesis, the target system is an example of an SME which is limited and less flexible to handle all of the proposed solutions. Therefore, the most effective factors for increasing the OEE percentage for the target system have been proposed to be selected based on the given priority.

Chapter 5

CONCLUSION

In this thesis, a novel agent-based control architecture is designed and developed which provided a distributed control for a target manufacturing system which has the properties and characteristic of a small and medium sized enterprise. The attained ability of distributed control for the target manufacturing system proved that the developed control architecture can facilitating the Industry 4.0 adoption for SMEs.

In order to follow the definition of an agent in the proposed control architecture, an agent-based control architecture with Master-Slave mechanism is selected. In the control architecture, agents task division and communication were the main concerns. The agent-based control architecture with Master-Slave mechanism included three layers which are Physical Resource layer, Physical resources control layer, and management layer.

It was the aim that the control architecture come up with enough compelling reasons and solutions which help SMEs to deal with their uncertainties about modifying their current control system. Therefore, a novel methodology is designed and implemented which involved all the required technologies and techniques to evaluate and improve the performance of the target system including the developed agent-based control architecture.

Implementation of the methodology successfully, helped to recognize all the problems and limitation associated with the target system integrated with the developed agent-based control architecture. Furthermore, as the part of the methodology objectives, performance of the system is measured accurately, and some modification is done to improve the performance of the system.

The methodology followed the Lean Six Sigma (DMAIC) approaches. As the Lean Six Sigma has five major phases, proper techniques and technologies are utilized to provide the requirement of each phase. For the “Measure” phase of Lean Six Sigma, an accurate combined time study technique is used to measure the target manufacturing system timing after implementation of the agent-based control architecture. The time study result helped to identify the problems and limitations of the system. Furthermore, the result of time study utilized in evaluation of the performance of the system in “Analyze” phase of Lean Six Sigma. The problems and limitations detected by analyzing the time study results showed the main solutions to overcome the problems.

Considering the requirement of the “Analyze” phase of Lean Six Sigma, Overall Equipment Effectiveness (OEE) standard is used to evaluate the performance of the system before and after implementation of the agent-based control architecture. In OEE Standard, the result of the time study is utilized to calculate the availability and performance of each resource available in the target manufacturing system. OEE percentage was a proper indication of the resources with more problem and limitation.

As the requirement of the “Improve” phase of Lean Six Sigma, after analyzing the time study and OEE percentages for each resource and entire system, some solutions to overcome the detected problem and limitations were defined. The solution for almost all the detected problems were depending on modification of the control architecture. Out of the factors which could be considered to modify the control architecture, distance between the resources and speed of motions were selected as the target factor.

ARENA as a simulation tool is utilized to create a simulation model of the real system with considering the implemented agent-based control architecture. The result of the simulation model was compared with the result of time study to validate the accuracy of the simulation model. All the solutions to overcome the identified problems and limitations were deploy on simulation model to investigate their impact on the system and its performance before implementation. The result of the simulation model after modification was utilized in OEE to evaluate the change in the performance of the system. Each of the solutions had different impact on performance of the resources. Therefore, for each solution a priority is given which shows the impact of each solution for each resource.

Implementation of the novel agent-based control architecture and methodology in this thesis, lead to reach to improved performance of the manufacturing system and may ensure SMEs to take the first and most important step toward the implementation of industry 4.0.

In this thesis the target system is a small-scale educational manufacturing system with a limited functionality period. Because of this selection, in the developed methodology, system observation and data collection were performed in a short period of time to prevent any damage to the system. As future work, the proposed methodology can be extended on real manufacturing systems without the mentioned limitations in order to perform all the evaluations over a long period of time.

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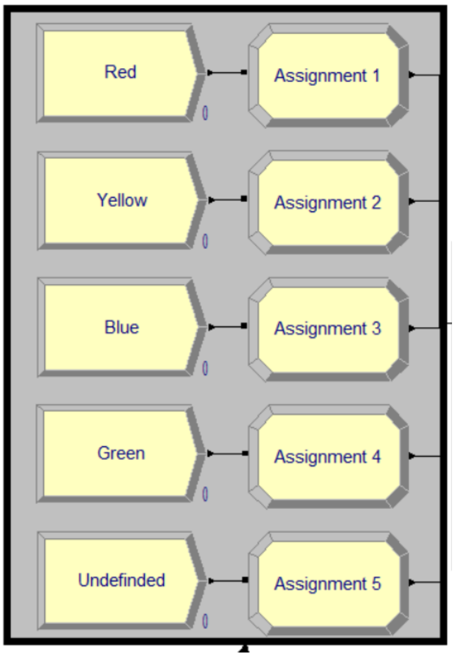
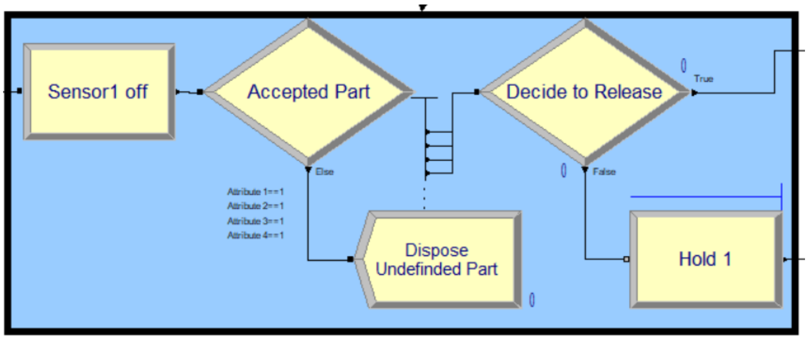
APPENDIX

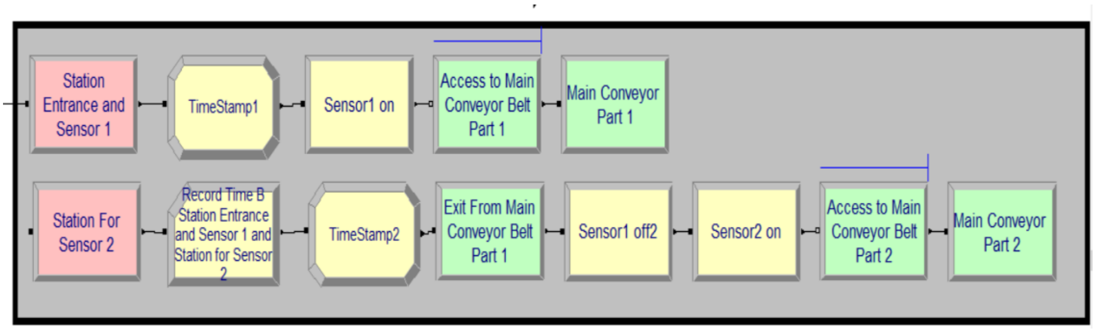
Appendix A: Arena Simulation control logic



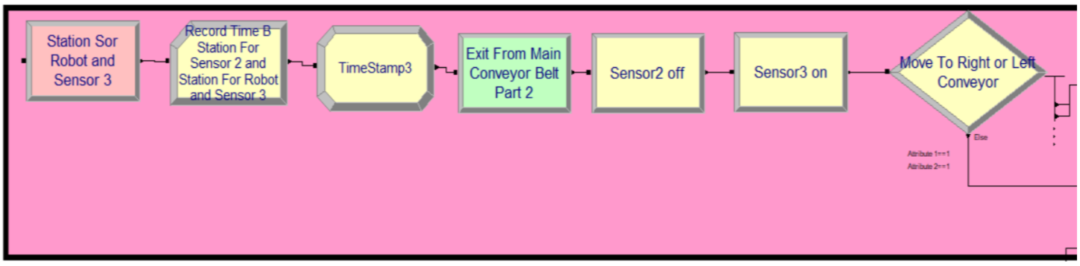
creating the Parts



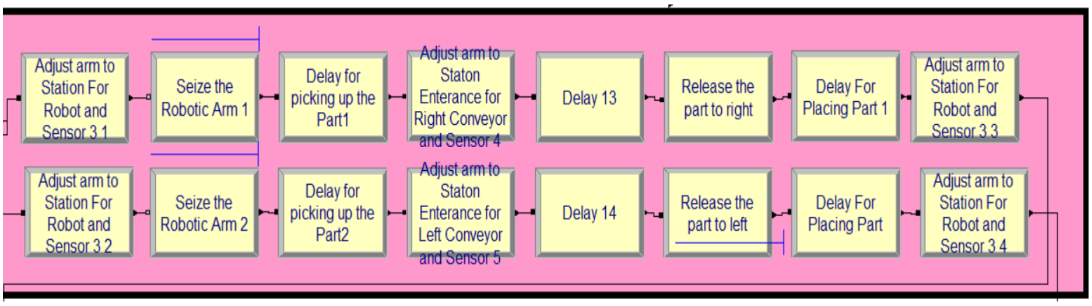
part loading to main conveyor



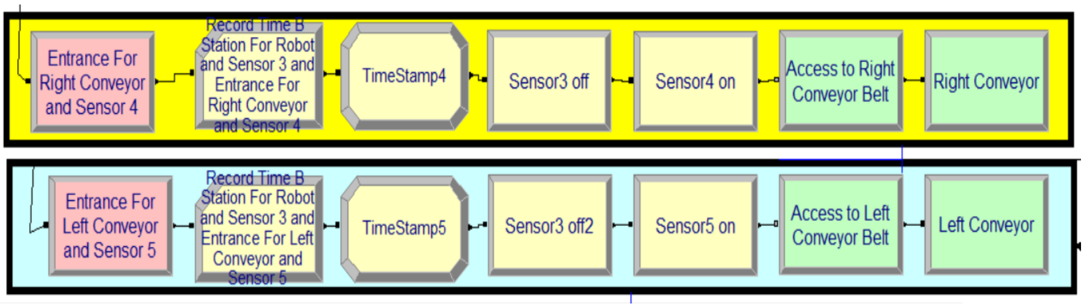
main conveyor



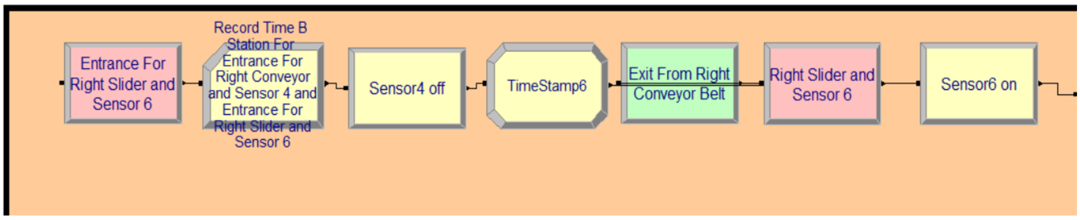
robot arm (Part 1)



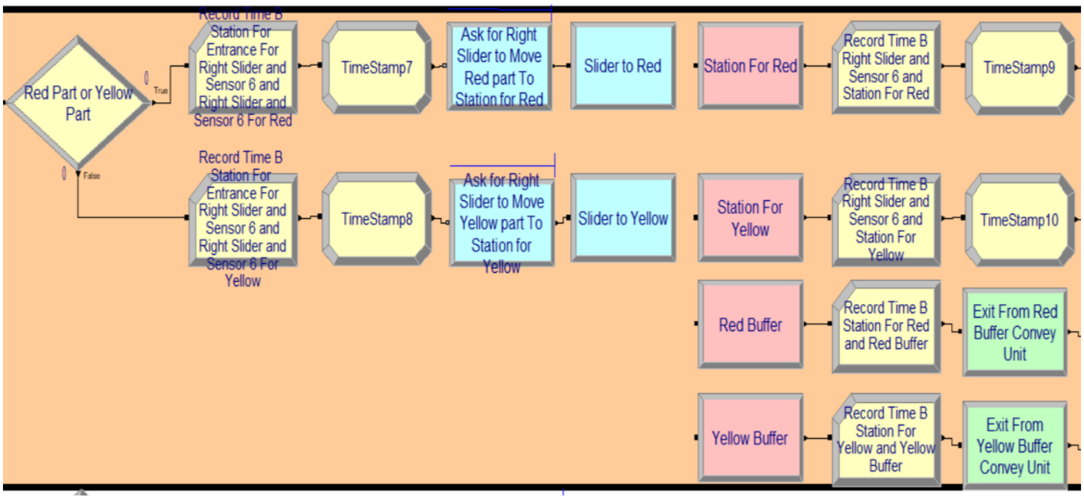
robot arm (Part 2)



side conveyors



right slider (Part 1)



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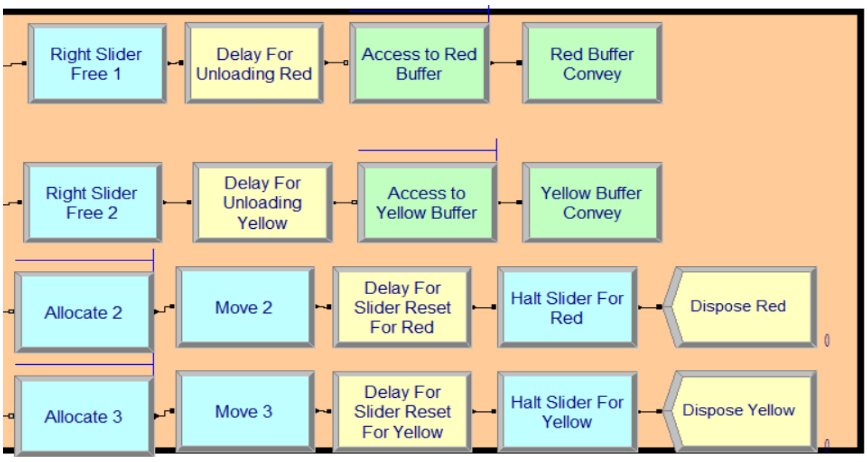
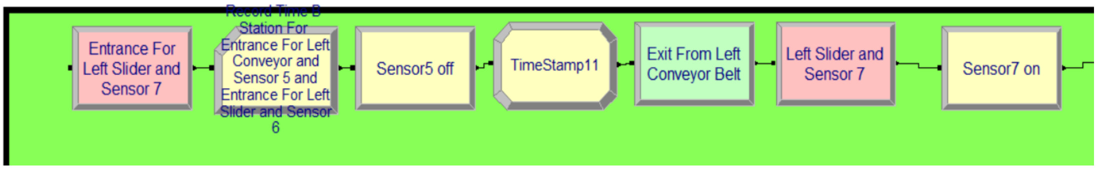


right slider (Part 3)



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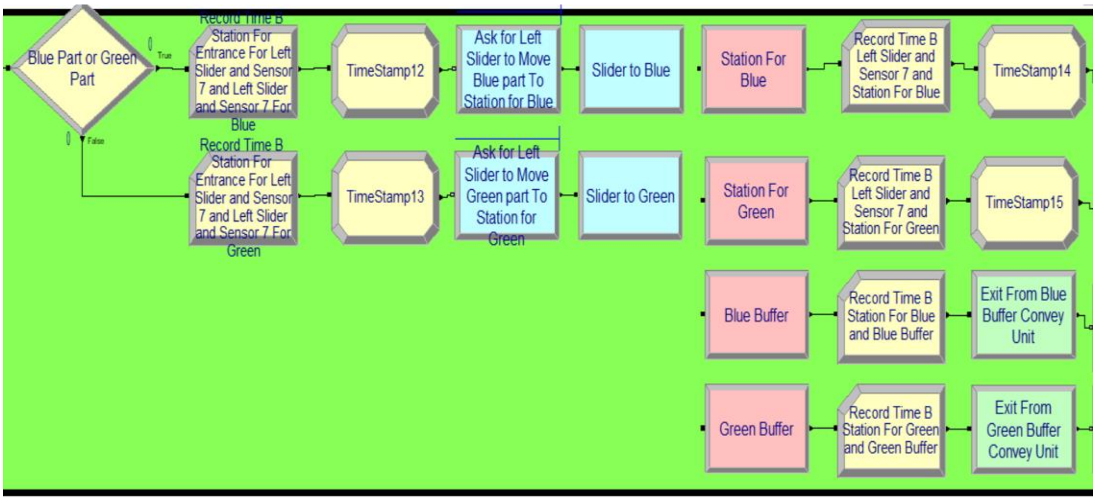

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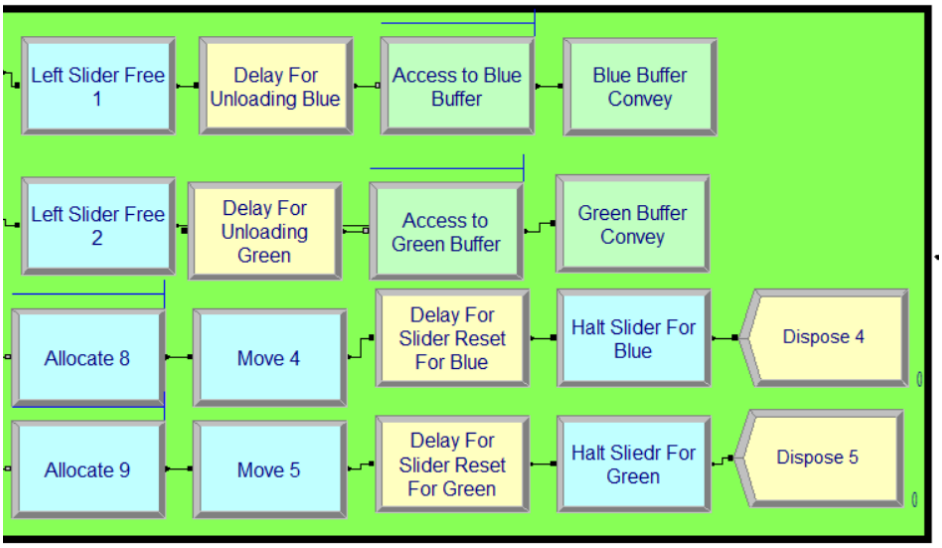

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