

University of Windsor

## Scholarship at UWindor

---

Electronic Theses and Dissertations

Theses, Dissertations, and Major Papers

---

7-11-2015

# A Capacity Planning Simulation Model for Reconfigurable Manufacturing Systems

Kourosh Khedri Liraviasl  
*University of Windsor*

Follow this and additional works at: <https://scholar.uwindsor.ca/etd>

---

### Recommended Citation

Khedri Liraviasl, Kourosh, "A Capacity Planning Simulation Model for Reconfigurable Manufacturing Systems" (2015). *Electronic Theses and Dissertations*. 5328.  
<https://scholar.uwindsor.ca/etd/5328>

This online database contains the full-text of PhD dissertations and Masters' theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email ([scholarship@uwindsor.ca](mailto:scholarship@uwindsor.ca)) or by telephone at 519-253-3000ext. 3208.

**A Capacity Planning Simulation Model for Reconfigurable Manufacturing Systems**

By

**Kouros Khedri Liraviasl**

A Thesis  
Submitted to the Faculty of Graduate Studies  
through the Department of Industrial and Manufacturing Systems Engineering  
in Partial Fulfillment of the Requirements for  
the Degree of Master of Applied Science  
at the University of Windsor

Windsor, Ontario, Canada

2015

© 2015 Kouros Khedri Liraviasl

# **A Capacity Planning Simulation Model for Reconfigurable Manufacturing Systems**

by

**Kourosh Khedri Liraviasl**

APPROVED BY:

---

Dr. Xiaobu Yuan  
School of Computer Science

---

Dr. Waguih ElMaraghy  
Department of Industrial and Manufacturing Systems Engineering

---

Dr. Hoda ElMaraghy, Advisor  
Department of Industrial and Manufacturing Systems Engineering

26 May 2015

## DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

### I. Co-Authorship Declaration

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

This thesis incorporates the outcome of research undertaken at the Intelligent Manufacturing Systems Center (IMSC) under the supervision of Professor Hoda ElMaraghy. The key ideas, primary contributions, experimental designs, data analysis and interpretation, were performed by the author, and the contribution of IMSC collaborators was primarily through the provision of the key concepts, directions and organization.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-author(s) to include the above material(s) in my thesis.

I certify that, with the above qualification, this thesis, and the research to which it refers, is the product of my own work.

### II. Declaration of Previous Publication

This thesis includes one original paper that has been previously published in peer reviewed conference, as follows:

Thesis Chapter	Publication title/full citation	Publication status*
Chapter 3, 4, 5	Khedri Liraviasl, K., ElMaraghy, H., Hanafy, M., Samy, S., 2015, A Framework for Modelling Reconfigurable Manufacturing systems using Hybrid Discrete-event and Agent-based Simulation, 15 <sup>th</sup> IFAC/IEEE/IFIP/IFORS Symposium Information Control Problems in Manufacturing, Ottawa, Canada.	Published

I certify that the above material describes work completed during my registration as graduate student at the University of Windsor.

I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices.

Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

## ABSTRACT

Important objectives and challenges in today's manufacturing environment include the introduction of new products and the designing and developing of reconfigurable manufacturing systems. The objective of this research is to investigate and support the reconfigurability of a manufacturing system in terms of scalability by applying a discrete-event simulation modelling technique integrated with flexible capacity control functions and communication rules for re-scaling process. Moreover, the possible extension of integrating the discrete-event simulation with an agent-based model is presented as a framework. The benefits of this framework are collaborative decision making using agents for flexible reaction to system changes and system performance improvement. AnyLogic multi-method simulation modelling platform is utilized to design and create different simulation modelling scenarios. The developed capacity planning simulation model results are demonstrated in terms of a case study using the configurable assembly Learning Factory (iFactory) in the Intelligent Manufacturing Systems (IMS) Center at the University of Windsor. The main benefit of developed capacity planning simulation in comparison to traditional discrete-event simulation is, with a single simulation run, the recommended capacity for manufacturing system will be determined instead of running several discrete-event simulation models to find the needed capacity.

DEDICATION

To My Parents and My Brother

## ACKNOWLEDGEMENTS

I would like to first of all, appreciate my supervisor, Dr. Hoda ElMaraghy, for her great support and directions throughout my master program and during my thesis preparation. I am very happy that I worked under her supervision in the last two years and it was quite great experience to work at IMS Center at the University of Windsor during this period.

My special thanks go to Professor Waguih ElMaraghy and Dr. Xiaobu Yuan for their careful reading of my thesis and their useful and valuable comments on my thesis.

I acknowledge my supervisor for providing the Research Assistantship (RA) and the Department of Industrial and Manufacturing System Engineering (IMSE) for Graduate Assistantship I received during my graduate studies.

I also want to appreciate IMSC collaborators, Dr. Mohammad Hanafy, Dr. Sameh Badrous and Dr. Mohamed Kashkoush, for their helpful advice into my thesis preparation.

My best appreciation also rests with my parents and my brother for their great mental and emotional support during my studies at the University of Windsor. I also appreciate the help and advice of my best friends, Mr. Javad Navaei, Ms. Maral Zafar Allahyari and Mr. Mostafa Pazoki during the preparation of my thesis.



## TABLE OF CONTENTS

DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION ..	iii
ABSTRACT .....	v
DEDICATION .....	vi
ACKNOWLEDGEMENTS .....	vii
LIST OF TABLES .....	x
LIST OF FIGURES .....	xi
<b>CHAPTER 1: INTRODUCTION</b>	
1.1. Research Motivation .....	1
1.2. Research Objectives .....	2
1.3. Scope .....	3
1.4. Capacity Planning for Reconfigurable Manufacturing Systems .....	4
1.5. Manufacturing Systems Simulation .....	4
1.6. Manufacturing Industry Needs .....	5
1.7. Thesis Statement .....	6
1.8. Thesis Structure .....	6
<b>CHAPTER 2: LITERATURE REVIEW</b>	
2.1. Introduction .....	8
2.2. Production Capacity Planning for RMS .....	8
2.3. Manufacturing Systems Control Methods .....	10
2.3.1. Holonic Control of Manufacturing System .....	10
2.3.2. Multi Agent-based Control for Manufacturing Systems .....	15
1. Scheduling and Production Planning .....	15
2. Programmable Logic Controllers and Function Blocks .....	23
2.4. Simulation Modelling Platforms for Manufacturing Systems .....	24
2.5. Reconfigurable Manufacturing Systems Modelling Techniques .....	28
2.6. Hybrid Simulation Methods for Manufacturing Systems Control .....	28
2.7. Concluding Remarks .....	29
<b>CHAPTER 3: METHODOLOGY AND MODEL DEVELOPMENT</b>	
3.1 Introduction .....	32
3.2. Capacity Planning Simulation Methodology .....	32
3.3. Simulation Modelling Framework for Agent-based Integration .....	35
3.4. iFactory .....	37
3.5. iFactory Capacity Planning Simulation Model Development .....	38
3.6. iFactory Simulation Model Development Using Agents .....	42
<b>CHAPTER 4: EXPERIMENTAL RESULTS AND DISCUSSION</b>	
4.1. Introduction .....	52
4.2. Simulation Scenario Using DES Only .....	53
4.3. Simulation Scenarios for iFactory Capacity Planning .....	54
4.4. Potential Extension of the Simulation Model .....	56
4.5. Discussion .....	58
<b>CHAPTER 5: CONCLUSIONS</b>	
5.1. Conclusions .....	63
5.2. Engineering Thesis Questions .....	65
5.3. Future Works .....	67
<b>References</b> .....	69

VITA AUCTORIS .....	74
---------------------	----

## LIST OF TABLES

Table 1. Process plan and sequence of operations .....	41
--	----

## LIST OF FIGURES

Figure 1. Overall design of PROSA Reference agent architecture .....	11
Figure 2. Developed holonic architecture of RMS .....	17
Figure 3. Behavior Model for the Product Agent .....	20
Figure 4. Developed Multi-agent System for the Washing Machine .....	21
Manufacturing	
Figure 5. A-0 IDEF0 functional model of capacity planning .....	33
simulation modelling approach	
Figure 6. Coding scenario for the system scalability .....	34
Figure 7. A-0 IDEF0 Functional Model of Hybrid Agent-based .....	35
Discrete Event Simulation Modelling	
Figure 8. iFactory Intelligent Flexible Assembly System .....	38
Figure 9. Capacity Planning Simulation Model .....	39
Figure 10. Logic rule between different system modules .....	43
Figure 11. AS/RS Agent Model .....	44
Figure 12. Robot Assembler Agent Model .....	45
Figure 13. Manual Assembler Agent Model .....	46
Figure 14. Quality Control Agent Model .....	46
Figure 15. Product Agent Model .....	47
Figure 16. Part Resources Agent Model .....	48
Figure 17. Transportation Agent Model .....	48
Figure 18. Desk Set product variants and structure .....	49
Figure 19. iFactory Model for Discrete-Event Simulation .....	51
Figure 20. Discrete-event simulation only production scenario .....	53
Figure 21. iFactory capacity planning simulation scenario .....	54
Figure 22. Case study ‘A’ capacity planning simulation results for 5 .....	55
orders per minute arrival rate	
Figure 23. Case study ‘A’ capacity planning simulation results for 10 .....	55
orders per minute arrival rate	
Figure 24. Case study ‘A’ capacity planning simulation results for 15 .....	56
orders per minute arrival rate	
Figure 25. Case study ‘A’ capacity planning simulation results for .....	56
probabilistic arrival rate	
Figure 26. Example of potential agent rules for robot assembly station .....	57
Figure 27. Discrete-event simulation scenario with the embedded robot .....	58
agent	

# **CHAPTER 1: INTRODUCTION**

## **1.1. Research Motivation**

Customers with everyday changing demands are requesting variety in products from manufacturing companies frequently without any pre-defined sequences and to be completed in short periods of time due to the need for new functions and features in products. Uncertainties similar to these occur in every manufacturing industry due to different market segments and regions with different certification requirements. As a result of these changes in product demands, product variety can be created significantly. Materials and technologies are renewed frequently to create required and new product features and provide the possibility to challenge other manufacturers and retailers, so they can compete with them in terms of new products, new customers and developing new markets for high variety creation. Economical benefits and customers' value improvements are important for manufacturing companies. They are dealing with variety of changes in products and services to provide more customized and personalized products with different functions and features for their customers to satisfy their needs (ElMaraghy et al., 2013).

Reconfigurable Manufacturing System (RMS) is a flexible enabler and convenient manufacturing paradigm for variety production of parts and products by changing the system for producing the new product variants. In this system, rearrangement of system's hardware and software modules should be quickly and reliably completed. Because of the changing environment for the system, several system modules need to change their functionality rapidly. For this matter, specific and required software modules for particular and required applications need to be plugged into the system (i.e. plug and play features). So, in this way the possibility of the production system obsolescence will be reduced. The open-ended nature of the system will help to improve system performance continuously by utilizing and integrating new technology into the system. Reconfiguration will quickly enable the production of new products and apply possible changes to product features in order to meet customer demands. There will be no need to replace the entire system with a new system when using this manufacturing strategy

(Mehrabani et al., 2000). Consequently, the most significant objective of RMS is to provide required functionality and capacity for the system in the exact time as needed (ElMaraghy, 2005).

A manufacturing system should have the following key features and capabilities to be considered as reconfigurable (ElMaraghy, 2005), (Koren and Shpitalni, 2010):

- **Modularity:** Modular design of all hardware and software system components in the manufacturing system
- **Integrability:** Enhance system design and functional components to be capable of integrating future new technologies into the system
- **Convertibility:** Enable quick product changes and fast adaptation to future new products
- **Diagnosability:** Quality and reliability problems identification quickly and eliminate sources of these problems
- **Customization:** Make system design capable and flexible of compatibility with desired applications.
- **Scalability:** Having changeable capacity considering time and cost constraints.

In conclusion, in order to provide the customers of a manufacturing company with their customized or even personalized product orders, there is a constant need for an effective design of a manufacturing system which will respond to customer order changes and enable required system scalability, convertibility and reconfiguration capabilities. In the next section the objectives of this research are specified.

## **1.2. Research Objectives**

According to the earlier discussions, the frequent changes in product demands, product structures and manufacturing processes would affect controlling procedures of the manufacturing system and it needs management regularly. The objective of this research is to build a discrete-event simulation model integrated with capacity control rules for a reconfigurable manufacturing system to simulate the scalability of the system in terms of number of needed machines during different stages of production which mainly depend on maximum queue capacity dedicated for each workstation. Moreover,

the possible frequent system stops and blockage caused by the several bottleneck possibilities for any of workstations will be effectively decreased with this methodology. As a possible extension for enabling automatic change capability of reconfigurable manufacturing systems, holonic control system architectures and multi agent-based modeling principles at the same time of using discrete-event simulation method would enable customer demand changes to be adapted in the most effective possible way.

In the development stage of considering alternative simulation modelling approach, object-oriented design framework of the existing manufacturing system using UML state charts would give an opportunity for modelling the reconfigurable manufacturing system using agents identification in the system which can be simulated in AnyLogic multi-method simulation modelling platform to find about how the reasoning engine of each agent (i.e. building block of the manufacturing system) will behave in collaboration with other agents in the system and making different behaviors according to the rules that is defined for each agent. These rules are capable of being changeable, reusable and renewable when the manufacturing system is facing changes in production requirements such as the introduction of new resources and processes to the system for manufacturing a new product considering both availability and capability of the manufacturing system components to produce the new products.

### **1.3. Scope**

The scope of this research is on shop floor production control for manufacturing assembly systems (i.e. iFactory Intelligent Assembly System) in order to build a modular, scalable and variant-oriented control system using discrete-event simulation modelling techniques and by getting the knowledge from autonomous agent-based system structure for equipment and resources control to develop an adaptive, changeable and reconfigurable production system. The products that are going to be manufactured by this proposed simulation model are needed to be designed in a modular way that can easily change the assembly or disassembly processes in case of having unplanned changes in customer demands rate. Moreover, this modelling approach is more useful for the manufacturing systems that are going to produce medium to low level amount of customized or even personalized products. Modelling the chaotic behaviour of the

manufacturing system in terms of illustrating required number of machines for each of the stages of manufacturing processes and smooth flow of the production are expected from this work. Changeable configuration on the real-time basis requires additional effort of programming algorithms and agent rules which is not expected to be done in this research work. In the next section, the need for capacity planning of reconfigurable manufacturing systems is explained.

#### **1.4. Capacity Planning for Reconfigurable Manufacturing Systems**

Scalability is one of the significant features for a manufacturing system that can facilitate adding, removing or modifying different workstations or machines and enable the reconfigurability of the manufacturing system. The main purpose of a scalable production system is to adjust the performance measurement metrics such as throughput and waiting time. Using modelling techniques for capacity planning such as system dynamics simulation and mathematical programming is beneficial for finding a cost-effective solution to handle the changes associated from different customer demands (Wang and Koren, 2012). During the entire process of preparing a scalable production plan, it has to be noted that in which part and at what exact time the re-scale of the system should happen depend on maximum queue capacity for different stations, maximum allowable cycle time for production of each product variants and several other production constraints. In the current literature of the capacity and scalability planning for reconfigurable manufacturing systems, there is no specific way to find the number of needed machines and determine the required number of them with a single simulation model run during different time periods. One of the main contributions of this research is to examine the possible solutions for this problem using a new technique of discrete-event simulation modelling integrated with resources pool functions and communication rules.

#### **1.5. Manufacturing Systems Simulation**

There is a significant need to utilize simulation tools and software to create a simulation model of the system, for system's design evaluation and monitoring performance of operations and processes in the system. Various problems are difficult to



view and realize in a real-world manufacturing system without using effective simulation. A simulation model of a manufacturing system includes a set of rules like equations and flowcharts to define the way the system is modeled and to help understand and evaluate the changes that may occur into the system in the future in terms of system structure enabled by different changes in products and processes. Also, simulation is useful for executing discrete and continuous changes in the system and should be executed when time dynamics is of high influence for dealing with the complex problem (Borshchev and Filippov, 2004).

Discrete Event Simulation (DES) is a tool and technique to realize and investigate dynamics of manufacturing systems. Different alternatives of system configurations can be analyzed by this highly flexible and capable tool which can execute different strategies and perform a variety of decision making techniques to model a manufacturing system (Negahban and Smith, 2014). Agent-based Simulation on the other hand, can build autonomous and co-operative components in manufacturing systems called agents in order to visualize and monitor the behaviors of each agent in different production scenarios. Multi agent-based simulation software platforms used in the design and implementation phases of Holonic Manufacturing System, are of high importance due to the needs for determining changes in functions of inputs, processes and output of the manufacturing system through simulation (Barbosa and Leitao, 2011).

## **1.6. Manufacturing Industry Needs**

Today's manufacturing industries need to modify their system structure by designing manufacturing system modules and examine the reconfigurability of their proposed system according to the requirements of Reconfigurable Manufacturing Systems and benefits of manufacturing system simulation modelling techniques. The implementation process for the reconfiguration of the system needs to be investigated by simulating the system using applicable software (e.g. AnyLogic) to analyze different changes as needed and support the most possible features of customer requirements and variety of demands and products. Clear definition of each control elements using simulation modelling principles and determining rules for controlling the system are required to attract intelligence to the manufacturing system. Design and implementation of this new

methodology to satisfy most of possible customer needs is a critical challenge that the manufacturing industries need to overcome and find the possible and effective ways to come up with an intelligent manufacturing system model which reduce cost, time, effort and energy for frequent system changes and modifications which increase productivity, value creation and satisfaction.

In addition, there are several reasons that this research is conducted and several benefits that industries can acquire. First of all, there are different customers for a manufacturing company with different demands (i.e. order arrival rates) and requirements who want to have the ability to customize or even personalize their own products and this way each customer can have own desired unique products. According to that, the ultimate goal of each manufacturing company is to increase the profit to its highest possible level and decrease the costs of production to its minimum feasible level. Intelligent Manufacturing Systems techniques, technologies and knowledge are needed to be utilized in the current industries in order to shift from mass production, which is no longer effective, to mass customization and personalization. Using this way of manufacturing system development, both customers with different needs and manufacturing companies with the ultimate goal of maximizing their profits without jeopardizing their customer's requirements and quality can benefit at the same time.

### **1.7. Thesis Statement**

The following is the thesis statement for this research:

The new developed discrete-event simulation model integrated with resources pool functions and communication rules will help manufacturing systems adapt to the changing customer demands and provide them with a scalability and capacity planning solution to determine recommended number of machines for different time periods which has several advantages in terms of controlling smooth flow of production.

### **1.8. Thesis Structure**

The next following parts of the thesis include, chapter 2 which illustrates a literature survey on several research works that have been done on production capacity and scalability planning for reconfigurable manufacturing systems. Moreover, other

production control methods for reconfigurable manufacturing systems such as holonic and multi agent-based control including scheduling and production planning applications, programmable logic controllers and function blocks and applications in agent-based simulation modelling are discussed. Concluding remarks and research gap are explained in this chapter as well. In chapter 3, the proposed capacity planning methodology and model development procedure are comprehensively explained and discussed. Also, in chapter 3, the case study which is iFactory intelligent assembly system as well as AnyLogic multi-method simulation modelling software which is used for this case study, are explained and discussed. Furthermore in chapter 4, experimental results and relevant discussions are provided. In this chapter the simulation model of the capacity planning methodology is examined through different production scenarios, also the possibility for the potential extensions of the current simulation model to an agent-based model are investigated. Finally, in chapter 5, conclusions, contributions and benefits of the proposed modelling technique are explained as well as research thesis questions and future works.

## **CHAPTER 2: LITERATURE REVIEW**

### **2.1 Introduction**

In this chapter, literature survey and discussions on several research works that have been done on production capacity planning for reconfigurable manufacturing systems are specified. Moreover, holonic and multi agent-based control of manufacturing systems as other relevant methods for production control of flexible and reconfigurable manufacturing systems are explained. Also, applications of these research areas in scheduling and production planning, programmable logic controllers and function blocks as well as different simulation modelling techniques for manufacturing system are comprehensively discussed.

### **2.2. Production Capacity Planning for Reconfigurable Manufacturing Systems**

Gyulai et al. (Gyulai et al., 2014) explored the requirements for the capacity planning of dedicated manufacturing systems and reconfigurable assembly lines and made comparisons in terms of customer demand changes. They have presented an integrated approach of using discrete-event simulation and machine learning method for the capacity management of low-volume products with the extension to high volume ones which is transferred from a dedicated manufacturing system to a reconfigurable assembly line in order to reduce the system complexity as well. In this modelling technique there are limitations in terms of time of the simulation model which is limited to some predefined periods and because of the increased complexity cannot be set to infinity. By applying this methodology to a real-life industry case study, it has been realized that reasonable amount of production cost can be reduced and saved.

In (Elmasry et al., 2014), a system dynamic simulation modelling approach is introduced for capacity scaling of reconfigurable manufacturing systems. In this work, several scaling scenarios and best applicable policies for the production capacity are examined and selected based on the consideration of random behaviour in the amount of orders and minimizing the cost of the production and inventory.

Reconfigurable Manufacturing System (RMS) capacity planning in terms of system scalability is discussed and examined in (Deif and ElMaraghy, 2006). Based on their approach, delay time that would happen for the ramp up of the new system configuration because of the new product families is reduced which directly decreased the number of work in process products by introducing dynamic aspects of the scalability into the system. In the other similar work (Deif and ElMaraghy, 2007), minimum level of scalability requirement for a reconfigurable manufacturing system has been determined by a system dynamics approach in order to improve the performance of the system and reduce the work in process level. Moreover, this system dynamic simulation approach is compared to several other introduced capacity planning strategies for determining the applicability of the proposed model.

In the proposed mixed integer mathematical model by Ossama et al. (Ossama et al., 2014) for the formation of the cell configurations in a reconfigurable manufacturing system, each family of products have its own dedicated system configuration that can achieve minimum setup cost and travelling time with the help of heuristic methods that are used in the model. In the proposed model routing flexibility in the larger size problems and real-time reconfiguration are not considered. In addition, Wang and Koren (Wang and Koren, 2012) introduced a different technique of reconfigurable manufacturing system scalability planning using genetic algorithm procedure which the rescaling of the system can happen in cost-effective manner. In this approach, the total cost of the needed number of machines is minimized but other types of costs could be considered as well in this problem.

Ceryan and Koren presented (Ceryan and Koren, 2009), several manufacturing capacity planning models and strategies which are analyzed and compared for finding the optimal decision planning for production processes considering the cost of the investment for building a changeable manufacturing system. In this study the investment planning for the optimal capacity problem is formulated using mixed-integer programming technique. Moreover, in this problem two types of products with changeable demands are considered during uncertain demand periods. It is found that increasing the flexibility of the manufacturing system in terms of covering changeable processes is the better

investment alternative which is compared with the two other dedicated manufacturing system models.

The reconfigurable manufacturing system line balancing approach is argued by Son et al. (Son et al., 2001). In this work a scalability modelling methodology called, homogeneous paralleling flow line (HPFL) system, is introduced which is compared to the transfer line production system model. The new proposed approach could be an applicable alternative when there are variable and uncertain demands for the transfer line system beyond the deterministic level and it will make the rescaling of the production easier than before. According to the cost estimation of the new proposed method, it is found that change capability of the system can provide a competitive solution for the scalability planning of reconfigurable manufacturing systems.

Manufacturing systems scalability need to be designed and operated properly and effectively and the relationship of scalability to manufacturing systems changeability, flexibility, reconfigurability and robustness was discussed by Putnik et al. (Putnik et al., 2013). Also, industrial applications of scalability for manufacturing system architectures, manufacturing systems hardware/equipment and information control systems and technologies are specified. Moreover, scalability has direct impact on product and process planning of manufacturing systems which creates complicated system and need to be managed efficiently.

## **2.3. Manufacturing Systems Control Methods**

### **2.3.1. Holonic Control of Manufacturing System**

Other production control techniques exist that support the reconfigurability and changeability of the manufacturing systems. Design of a Holonic Manufacturing System has been discussed by Valchenaers et. al (Paul et al., 1998) from the manufacturing control point of view. The Holonic control system embedded into the baseline of a manufacturing system has several essential steps in design and implementation which has been addressed by designing control software for the system.

Based on the PROSA (Product-Resource-Order-Staff Agents) Holonic manufacturing control system reference architecture (Van Brussel et al., 1998), there should be existing three types of basic holons called resource holon, product holon and order holon in the architecture of a manufacturing control system in order to be functioning in an agent-based holonic control way (Figure1). Resource holons represent machines, conveyors, pallets, components, raw materials, tools, tool holders, material storage, workers, etc. of a manufacturing system to enable each of them in acquiring the knowledge about the procedure of resource allocation. Product holons provide the knowledge of required process plans, bill of material, design, quality assurance procedure, etc. for manufacturing the desired products ordered by customers. Customer orders and different types of system processing orders can be handled by order holons. These three basic holons will collaboratively share the knowledge of production, process and process execution between each other to control the manufacturing system in the most appropriate way. The object oriented design of the system using UML (Unified Modeling Language) based on aggregation and specialization design principles is useful in terms of providing a framework of the activities, attributes and communications in each holon and other related holons. This has been implemented on the Flexible Assembly System (FAS) test bed created in K.U.Leuven University for conducting research on Holonic Manufacturing Systems (Van Brussel et al., 1999).

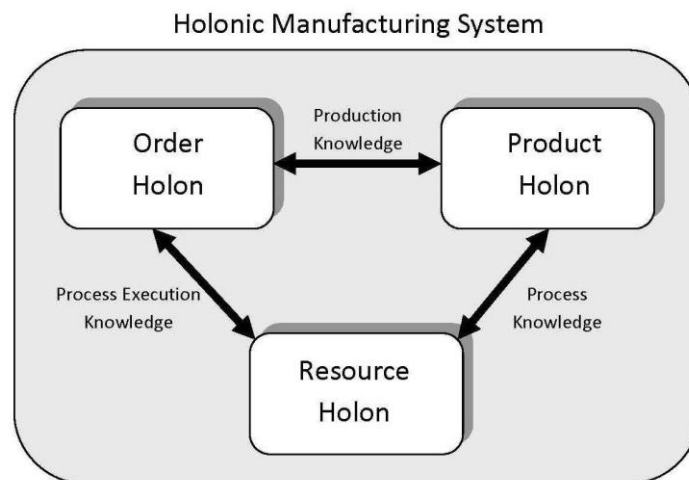


Figure 1. Overall design of PROSA Reference agent architecture [Reproduced from (Van Brussel et al., 1999)]

The InterRRaP agent architecture introduced three basic production planning layers as system control hierarchies including co-operative planning layer, local planning layer and behavior based layer (Fisher, 1999). Distributed decision making techniques were highlighted in the context of shop floor control in order for having an agent-based design of the Holonic Manufacturing System presented by two case studies.

Holonic Multi-cell Control System (HoMuCS) architecture as an enabler for holonic control of shop floor control systems would provide system agility in terms of changeable operations and changeable structures and configurations (Langer and Alting, 2000). Also, the principles of manufacturing engineering and software engineering (i.e. object oriented system design with UML standard) are combined together for the presence of Holonic Manufacturing System concept which provides products with high variety and low volume.

Plug and Produce concept for an assembly system which can facilitate reconfiguration when product changes occur, has been introduced by Arai et al. (Arai et al., 2001). Moreover, sequencing of production for the assembly of the product family reaches according to negotiations between assembly stations using Contract Net Protocol (CNP).

Multi agent-based control of an engine assembly plant using agent-oriented design techniques is provided in a holonic control system which significantly improved system output and robustness (Bussmann and Sieverding, 2001).

Manufacturing control system modelling can be formally implemented by UML class diagrams for static aspects and Petri Nets for Dynamic behavior aspects (Leitão et al., 2003). ADACOR (Adaptive Holonic Control Architecture for Distributed Manufacturing Systems) would enable the manufacturing control system to create a model of the production plan using Petri Nets to model Product Holon, Task Holon, Operational Holon and Supervisor Holon as the main holonic control elements of that architecture.

A holonic approach for industrial control systems has been introduced due to the needs for more flexibility, reactivity and efficiency in the complex environment of manufacturing systems as well as the need for control systems integration (Blanc et al., 2008a). This reactive and reconfigurable control system is based on PROSA architecture



which is also compatible with Holonic Component Based Architecture (HBCA). According to the tasks are done by different types of resources in the system such as supplying, disassembling, transforming or assembly, a resource holon topology has been proposed. Because there might be different types of manufacturing control problems existing, there would be specific heuristics used in order to solve those problems in each micro model such as scheduling /packing problem for the raw material cutting machine. Moreover, there will be order holons responsible for controlling different orders in conjunction with relevant resource holons as networks which are known as runtime dynamic elements. For the validation purposes, a case study in American Glass Product (AGP) Company has been implemented with aim of offering highly customized products and Arena simulation software has been used for examination of the system as well as prevents the redundancies. In order to ensure component availability for orders in time limit constraints on task scheduling, a mechanism has been proposed for synchronizing the execution of manufacturing orders. This approach is based on heterarchical and product-centered control architecture. A Multi Agent system would support these mechanisms and algorithms for developing the manufacturing control system. This system will allow the management system to be integrated and interfaced with enterprise resource planning and the physical system. The proposed HMS/MES system is capable of handling discrete-event based manufacturing systems.

Girret and Botti (Giret and Botti, 2009) reported that developed numbers of holonic control architectures and holonic control algorithms exist but they lack in methodologies for holonic manufacturing system. Software engineering principles would be used in each development stage in order to help system designers. The ANEMONA engineering approach has been discussed in this work which combining modeling concepts from distributed intelligent system development and specific modeling requirements of Holonic Manufacturing Systems. The negotiation between Client/User and high level HMS specifications indicates that a recursive analysis would be provided which will establish a set of basic elements and rules for assembly tasks. Also, there would be a Holon implementation stage for the purpose of producing Executable Code for the SetUp and Configuration stage as well as Operation and Maintenance stage for system's function maintenance. In fact the proposed approach will provide the system designers

with Holonic Manufacturing System special guidelines in every stage of development. It is needed to implement real-life industrial case studies utilizing agent-based simulation tool created by ANEMONA modeling entities. The connection between ANEMONA approach and other proposed agent platforms for holonic structures like JANUS platform is needed to be analyzed and reviewed.

Roulet and Ystgaard (Roulet-Dubonnet and Ystgaard, 2011) considered a flexible and reconfigurable assembly cell which uses Holonic Manufacturing System paradigm. Damped machining tools assembly has been considered as the case study which involves different types of changes frequently, so the automation would be the challenging part. The designed assembly cell consists of an assembly robot, a pallet transport system, the feeding equipment such as custom elevator, and sensors such as stereo vision systems. The architecture of the real-time control system and mechanical design of the cell has been composed by taking advantage of Holonic Manufacturing System paradigm. In the proposed system communications would be through realization of the tasks and utilizing sensors for keeping an up-to-date view of their environment. According to the results of the system the required reliability, flexibility and reconfigurability of this type of manufacturing cells have been satisfied through Holonic Manufacturing System paradigm. Moreover, a transformed version of agent-based APROX concept have been used in this system instead of common PROSA and ADACOR architectures because they provide more adaptive control for small assembly cell. The results of running the system illustrated that the replacement of feeding equipment by new equipment or operators can happen without reprogramming due to the independency of assembly system from other feeder equipment, providing added flexibility through decoupling between assembly and feeding tasks, no need to modify the complex robot program when a new product would be added and modularity and maintainability of the system will be increased because of the control system has been functionally and physically distributed. Future research requires a complete pallet conveyor system to be added for creating new control holons and investigate the results.

As an application of Holonic Manufacturing Systems (HMS), leather manufacturing uses combination of two well known reference architectures for manufacturing (i.e.

PROSA and ADACOR) to overcome the existing production challenges in leather industries (Guță et al., 2013). Distributed modular architecture, decentralized control, intelligent, adaptive and reconfigurability are the main requirements for the leather production control system using holonic control architectures and Multi-agent systems concepts.

Tyre-manufacturing system, in another application, can be virtually controlled by taking advantage of ADACOR holonic control system reference architecture and using UML class diagrams and sequence diagrams for identifying each manufacturing holon and communication between holons for improving productivity of manufacturing processes (Jovanović et al., 2014). The object-oriented design of the system using JADE (Java Agent Development Environment) platform enabled the simulation model of holonic manufacturing system consisting of product holon, planning holon, control holon and operational holon to be developed which FIPA (Foundation for Intelligent Physical Agents) protocol is the communication language that has been utilized.

### **2.3.2. Multi Agent-based Control for Manufacturing Systems**

Literature on the manufacturing control solutions for reconfigurable manufacturing systems indicated that multi agent-based control systems offer potential alternatives for dealing with production changes caused by variety of production orders. These solutions also have the potential to be considered for capacity and scalability planning.

#### **1. Scheduling and Production Planning**

The Multi Agent-based Control System (MACS) for a car body paint shop in Daimler-Benz AG plant formed the MASCADA project for illustration of real world application (Bruckner et al., 1998). PROSA agent-based control architecture utilized object oriented design methodology (UML) to build the holonic model of the paint shop.

Real-time scheduling framework and the model for holonic production control architecture of an aircraft part production and assembly using object-oriented modeling techniques for facilitation of decision making process in scheduling of the system is presented (Sugimura et al., 1998).

A solution to the resource allocation problem and disturbance handling in manufacturing systems using ADACOR holonic architecture has been reached by Leitao and Restivo (Leitao and Restivo, 2002). Moreover, supporting changeable manufacturing would be enabled by supporting the heterogeneous agent architectures consisting of mobile agents and static agents to develop a dynamic manufacturing system fulfilling a variety of customer requirements (Wang et al., 2002).

Lim and Zhang (Lim and Zhang, 2003) proposed multi agent-based framework which will provide process planning and production scheduling integration. Dynamic resource optimization and reconfiguration platform for different alternative configurations would be provided by this framework. A Multi-Agent System (MAS) is studied by adopting autonomous agents capable of interacting and negotiating with each other in order to bid for the jobs and make critical decisions when process planning, scheduling and optimization problem/tasks will be raised. Moreover, Visual Basic (VB) programming language is utilized in order to implement the proposed framework and Microsoft Access is used for product database. Changes in customer demand and different circumstances have been analyzed which require different types of predefined agents in the system to react to these changes in a timely and effortless manner.

Multi agent-based control architecture for a Flexible Assembly Cell (FAC) using object-oriented system design and modeling techniques has been proposed (Fan and Wong, 2003). Furthermore, agentification approach to detail design the engine machining plant control system is illustrated by “plug and produce” concept of manufacturing using UML object-oriented design principles (Braatz et al., 2003). The same plug and produce concept has been applied to a washing machine flexible assembly plant which utilized multi-agent system design including Machine Resource Agent (MRA), Coalition Leader Agent (CLA), Transportation System Agent (TSA) and Human Machine Interface Agent (Onori et al., 2012). In addition, holonic agent-based control architecture for Reconfigurable Manufacturing Systems (RMS) based on the PROSA reference architecture is developed as illustrated in Figure 2 (Wang et al., 2005).

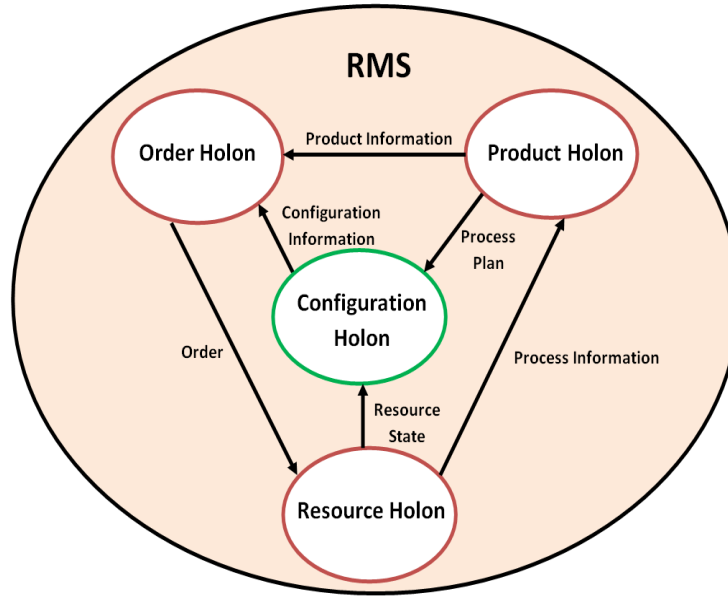


Figure 2. Developed holonic architecture of Reconfigurable Manufacturing System[Reproduced from (Wang et al., 2005)]

Configuration Holon is the additional added component to the PROSA agent-based control system which takes care of reconfiguration time, cost and efforts analysis in the system to produce the customized product. Function blocks and PLCs can be used for real-time agent-based control of each holon existing in the manufacturing system.

Product Holon, Task Holon, Operational Holon and Supervisor Holon has been developed for ADACOR holonic production control architecture based on the understanding from PROSA agent-based reference architecture concepts (Leitão and Restivo, 2006).

Distribution, autonomy and reconfigurability of a manufacturing system enabled by agent-based control of the production system include agent client, agent order management and agent resource (Lima et al., 2006).

Monstori et al. (Monostori et al., 2006) has conducted a research review of the new paradigm shift which is an agent based computation for building intelligent and distributed systems. Also, utilization of the software agents and multi-agent systems has been discussed in detail. The features of autonomy, responsiveness, modularity and openness of various agent technologies has been compared comprehensively in order to

know in what way and how these technologies would utilize distributed and imperfect information and knowledge resources for solving the likely conflicts and uncertainties in communication, collaboration and cooperation. Main barriers would exist in implementing agent technologies in traditional manufacturing systems such as scalability, safety and traditional software quality which will end up with the inconsistent functional operations globally and also affect the communicational functions. Researchers hope that agent-based technologies can overcome these issues. Facilitation of human needs through resource changes would enable the use of adaptive and knowledge based manufacturing system. Accordingly, it is essential to know how the agent based concept in different manufacturing scenarios would involve cooperative manufacturing. As it is claimed, the evolution process of the multi agent system concept is a hand in hand procedure where researchers would develop new technologies with that concept which is required by implementing new manufacturing disciplines.

The product Fischertechnik based educational shop floor platform has been developed (Barata et al., 2008) based on a multi agent based control architecture. This platform has various heterogeneous manufacturing modules which are agentified and a multi agent based coalition has been created in order to simulate the system. Moreover, it is founded that the system is capable of coping with product variety and process changes without any reprogramming. Each new module can be added to the system by introducing their skills to the system for use in the new product design. Also, the proposed educational platform is quite useful for dealing with different situations and problems rather than a real industrial case but it may lack in providing users and designers with all the challenges in a real system.

Holonic production control of glass production for automotive industry using PROSA agent-based reference architecture has been investigated in order to build a Manufacturing Execution System (MES) and scheduling model based on multi agent-based production techniques such as modeling the communication between agents using negotiation protocols like Contract Net Protocol (CNP) and Agent Communication Language (FIPA-ACL) (Blanc et al., 2008b).

In other work (Alsafi and Vyatkin, 2010), an ontology-based reconfiguration agent has been developed in order to achieve the fast reconfiguration of modular manufacturing systems. In order to deal with the challenges of today's manufacturing environment, the ontological knowledge of the manufacturing environment should be modeled and analyzed. Java platform has been implemented in conjunction with Eclipse IDE in the proposed model. Moreover, in order to have a representative for the ontological knowledge model, JENA (an open source java framework) has been utilized. Also, Pallet as a Java rule based OWL-DL reasoner has been taken into consideration in conjunction with Jena framework. The knowledge model will analyze the problem and generate the feasible solution for the new configuration using embedded agent controllers as sub-configurations.

Multi agent systems have several industrial real-life applications to deal with which are useful for allocating manufacturing resources optimally and schedule and control the manufacturing functional operations (Skobelev, 2011). Adaptive scheduling using multi agent technology and analysis of industrial multi agent solution functionality has been detailed for manufacturing and transportation applications. Multi-Agent Systems (MAS) and Holonic Manufacturing Systems (HMS) are the two paradigms for design of the complex, distributed and reconfigurable holonic multi-agent systems (HoloMAS) which is using concepts of bio-inspiration characterized by self-organization and evolution.

The work presented by Leitao and Rodrigues (Leitão and Rodrigues, 2011) adopts the Multi-Agent System approach as a tool for integrating production and quality control processes in washing machine production lines. This is a development aspect of the ongoing project called EU FP7 GRACE (integration of pRocess and quality Control using multi-agEnt technology). Moreover, the proposed architecture uses previous proposed multi-agent systems architecture such as PROSA, ADACOR and PABADIS-PROMISE which featured frequently used manufacturing processes. In addition, the general idea is to ensure real-time responsiveness and build an agent layer on top of current low-level control system that uses industrial control based on PLC running IEC 61131-3 control programs for providing intelligence and adaptation. Furthermore, petri net is used as a formal modeling tool for synthesizing the system specifications and

validating model correctness, for realization of structure and behavior of each agent. Petri net is a useful tool for simulating and evaluating different behaviors of complex adaptive systems with stochastic, flexible and distributed features which requires strong background in mathematics. Figure 3 illustrates the behavior representation of a product agent which consists of different time steps and can be expanded into more comprehensive sub-Petri nets which increase model complexity. In this way a top-down methodology will allow the modeling of behaviors for each agent as well as step by step system refinement for providing the hardware with system operation details.

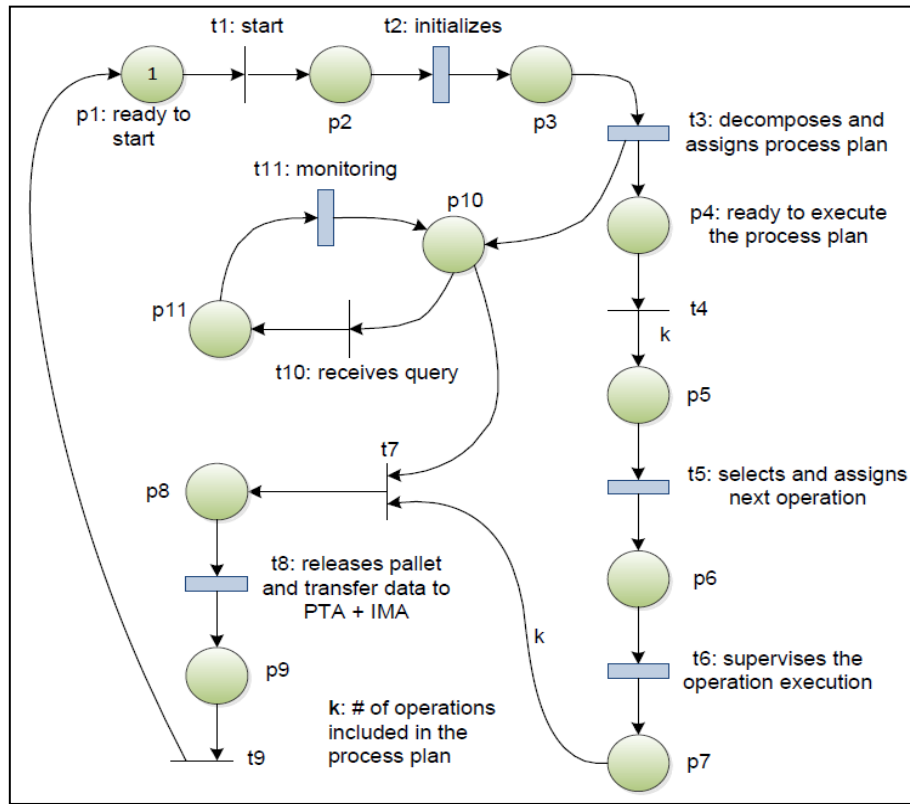


Figure 3. Behavior Model for the Product Agent [Taken from (Leitão and Rodrigues, 2011)]

The behavior of a multi-agent system is understood through the need to recognize interactions among individual agents and clarify the local behavior of them by using the concept of emergent behavior. This concept arises from the nature behavior where different entities would have simple behaviors with few numbers of rules and can generate complex systems. For instance, ants and bees regularly have very simple behaviors but the colonies will have smart and complex behavior as usual. In



manufacturing systems, the manufacturing processes have developed a kind of networking system for the matter of collaborations between agents with the purpose of supervision and control which each agent has its own objectives, behaviors, perceptive and cognitive capabilities. Moreover, beside of the embedded control algorithms for each agent, there is partial knowledge for them for solving the problems, but when they cannot solve the problem alone they collaborate and interact with each other for sharing their knowledge and skills. Figure 4 shows multi-agent system architecture where individual agents interact with each other.

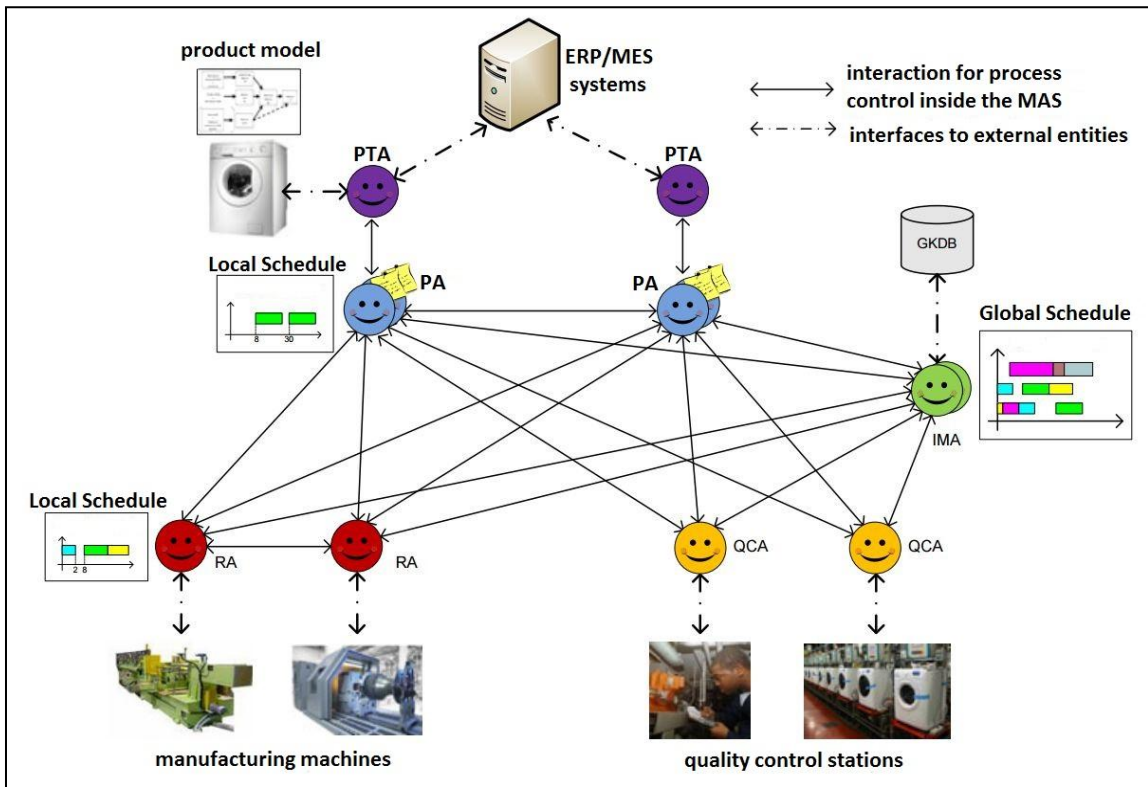


Figure 4. Developed Multi-agent System for the Washing Machine Manufacturing  
 [Taken from (Leitão and Rodrigues, 2011)]

This system is constructed to improve the production effectiveness and quality control procedures as well as decrease the production-line down-time and rate of defects. Moreover, the proposed system consists of micro and macro architectural levels. Agent architecture, agent functional class determination and individual agent's behavior are the representation at the micro level. Also, macro level would explain interaction among agents to understand the mechanisms for controlling production and quality tasks featured by a feedback control loop. In addition, JADE (Java Agent Development

Framework) platform has been used for the prototype of the model which includes PTA (product type agents), PA (product agents), RA (resource agents), QCA (quality control agents) and IMA (independent Meta agents). Agent interface determination using applicable ontologies in the agent systems need be considered for future studies.

Virtual model of a production line using a production scenario for a digital factory was presented (Matsuda et al., 2012). Plant panel, machine model and machine agents defined are necessary for virtual model construction. Product panel, process model and work piece agents are needed to be defined for control purposes. A prototype of the proposed system has been implemented using a cell phone production example and a production scenario application.

As it is investigated by Leitao et al. (Leitao et al., 2012) the offered Multi-agent systems solutions have the features of modularity, flexibility and robustness for enabling system responsiveness but lack in providing proper re-configuration and required system adaptability. In order to deal with this problem it was needed to develop effective adaptive systems considering nature and biology principles at the same time which enable the evolving manufacturing systems to deal with challenges of the complex control system that is going to be provided. To test the proposed approach, an automation case study in AIP-PRIMECA production center has been considered which exhibits promising, adaptive and reactive features of bio-inspired system for dealing with dynamic complex environments. With this insight, adaptive manufacturing systems can be developed with self - \* properties by combining different bio-inspired methods for obtaining adaptation, robustness, flexibility, scalability and reconfigurability.

Object-oriented programming has been discussed and investigated as an extension to agent-based control for the Reconfigurable Manufacturing System (RMS) through comparing the requirements for designing and modeling agents and objects in the system. The usefulness and advantage of object-oriented programming and design techniques have been compared with rest of the available methods (Graefe and Basson, 2014).

The ADACOR evolution approach is proposed and investigated by Barbosa et al. (Barbosa et al., 2015) in order to improve the self-organization process introduced by the

first version of the ADACOR methodology. The structural complexity of the manufacturing system was examined during the re-organization of system configuration for the adaptation to changes caused by market demands. In fact, the complexity indicator that is introduced in this work showed the ADACOR<sup>2</sup>, which is the improved version of the ADACOR, has the lower complexity and made improvements in terms of production throughput.

## **2. Programmable Logic Controllers and Function Blocks**

Holonic Manufacturing Systems (HMS) consider both event-driven real-time control strategies based on the IEC 61499 function block model [(Fletcher, 2002)] and deliberative non real-time distributed information processing based on multi-agent system (MAS) ideas. IEC 61499 Function Block will come in the low level control and decision making level as the basic framework which can collaboratively communicate with the high level decision making part which is the agent. Furthermore, synthesis of PLC IEC 61131-3 (Centralized, programmable and configurable) and DCS IEC 61804 (Distributed and configurable) [(John and Tiegelkamp, 2001)] standards will construct the IEC 61499 Function Blocks which can be utilized as an enabler for dynamically reconfigurable control and agile manufacturing. Through combining Holonic Manufacturing Systems requirements and IEC 61499 Function Block control architecture, Intelligent Automation architecture can be constructed.

Holonic Control of Engine Cylinder Head assembly plant known as Factory Broker Agent has led to design of a multi agent-based control system based on PLCs principles using IEC 61131 control standards and consisting of work piece agents, Machine Agents, Transport Agent and Communication Interface (Colombo et al., 2001). This case-study has been proved the real-life application of Holonic Control Systems and Multi Agent-based Systems application in manufacturing domain.

Balasubramanian (Balasubramanian et al., 2001) found that the traditional scan-based control system would not be suited for the holonic manufacturing system because of the endless changes and transformation (metamorphosis) of the system during its lifetime. A new system-level distributed control system was developed for this reason, which is

called metamorphic control system. Moreover, the engineering design of these software-centric metamorphic control systems have been addressed and created for a dynamic reconfigurable distributed multi-sensor based holonic system. In addition, a variety of functional levels is introduced in the proposed metamorphic control system which uses the emerging International Electrotechnical Commission function block standard (IEC 61499) in order to analyze and evaluate different behaviors of distributed control software components (agents) and the measurement of the industrial process. The requirements for responsiveness to the changes can lead to the distributed artificial intelligence approach at the planning and control level in order to achieve low-cost automation solutions and distributed computing platforms for manufacturers.

Application of Function Blocks for shoe production control using IEC 61499 standard is highlighted in the work of Carpanzano and Jovane (Carpanzano and Jovane, 2007). Mass customization of shoes was enabled with this tool by flexible transport system as well as flexible and reconfigurable machines.

The practice of the industrial control systems automation and real-time control using IEC 61499 function block technology and the unique advantages of this holonic control tool in comparison with other multi agent-based simulation techniques has been investigated (Vyatkin, 2011) and it is found that a combination between this new technology and existing current implemented multi agent-modeling techniques like UML modeling would help to adjust the control system development cycle in an effective way.

#### **2.4. Simulation Modelling Platforms for Manufacturing Systems**

Agent-based Modeling (ABM) is a useful tool when there are autonomous agents in the system want to deal with complex conditions such as frequent changes in the system enabled by different customer demands. Simulation of Agent-based Systems illustrates the behavior of each agent in the presence of system disturbances and provides the opportunities to try different software platforms for Multi Agent-based System modeling for production control purposes (Barbosa and Leitao, 2011). The washing machine agent-based production line example (Leitão and Rodrigues, 2011) can also be modeled in NetLogo multi agent-based modeling and simulation software platform as one of the

suitable educational case studies to clarify the behavior of agents in the manufacturing system from different production control scenarios perspectives.

Object Oriented Programming (OOP) is one of the significant tools that many researchers are taking into consideration when building Agent-based Modeling (ABM) frameworks for their manufacturing system. Moreover, object oriented design patterns are utilized by software engineers in order to simplify modeling of object in an agent-based system. In this system agents can be designed to have autonomous actions and make decisions by themselves when dealing with different environment situations. Because of that object-oriented design principles should be utilized to monitor and control agent behaviors such as Unified Modeling Language (UML) for high level representation of agents in the manufacturing system. Application Programming Interface (API) is used as a model maker and application framework constructs and manages communications, interactions and schedules for each agent as well as between different agents (Allan, 2010).

MASON (Multi-Agent Simulation of Neighborhoods) can be used as a Java-based discrete event multi-agent simulation toolkit which is useful and reliable software for multi-agent simulation applications such as swarm robotics, machine learning and social complex environments. High level of computational efforts for simulating a complex adaptive system can be developed and managed by this platform which requires several iterations of the simulation model to be executed.

NetLogo is a useful platform used when a graphical analysis and visual documentation of the simulation runs and results are needed. Designing and modeling high amount of autonomous agents using different rules and algorithms and based on Internet utilization at the same time would be the goal of this software in order to develop a complex system. This software platform would enable the understanding of agent behaviors at micro-level and macro-level as well as their relationships through acquiring necessary communications skills between agents.

RePast (Recursive Porous Agent Simulation Toolkit) originated from Social Science Research Computing Lab located in University of Chicago for modeling agent based

systems in the social sciences area of research. This software is based on the Swarm concept and uses that notion for library code creations and data collection to execute simulation models based on agents.

JADE (Java Agent Development Framework) uses Foundation of Intelligent Physical Agents (FIPA) properties for the ease of performance for distributed multi-agent systems. Graphical User Interfaces (GUI) controls agent configurations and distribution of agents for different machines. A network of agents based on Java would be created capable of handling changes in system configuration and agent functions.

SeSAm (Shell for Simulated Agent Systems) developed by University of Wurzburg is an agent based simulation tool based on Java to design complex models in an easy and simplified way and illustrate emergent behavior of agents dealing with different kinds of environments and situations. Emergent behavior can be defined as a behavior in software agents which will be created through coordination with other agents and is not strictly generated from each individual agent. Consequently, emergent behavior can be mentioned as collective behavior (Zhengping et al., 2006). Visual agent modeling helps to define situation and environment for the model in this software, through building and programming rules for them and build a graphical simulation for further analysis. Distributed simulation of SeSAm can also be compatible with JADE by utilizing FIPA plugin prepared for the software which is useful for modeling communication between agents.

A practical system framework is proposed and developed by Kotak et. al (Dilip et al., 2003) which developed a holonic system design of operations in a distributed manufacturing system environment by utilizing multi-agent systems (MASs) and agent-based simulation techniques. Holonic control, virtual simulation and integration between human and the manufacturing system are the main components of the proposed system which JADE<sup>TM</sup> platform is used for the holonic control as the entire system's brain. A conceptual material transport system has been taken into consideration to validate the proposed idea. Also robustness, autonomy, cooperation and coordination of the system which are the main characteristics of the Holonic Manufacturing System (HMS) has been examined and evaluated. JADE<sup>TM</sup> FIPA-compliant open source is used for holons

intelligent agent technology realization. In order to have a communication among holonic agents and message expression, FIPA-ACL embedded with XML is adopted. A 2D virtual simulation as well as a 3D discrete event simulation model using QUEST<sup>TM</sup> was implemented in the case study, which was enabled by the holonic manufacturing system paradigm. As the environment and system change enabler, the human user can be the source of dynamic communication, system disturbance and system design in the changing environment. Also, there would be an ongoing and continuous process for applying holonic techniques in energy industry. Moreover, procedures in holonic decision making and system modules learning ability can be facilitated by using artificial intelligence technologies.

Manufacturing Agent Simulation Tool (MAST) has been developed and applied to make an agent-based model of Cambridge Gift Box Holonic Packing Cell using JADE and JACK agent platforms (Mařík et al., 2005). The agents that are considered in the model consist of RFID reader agent, gate agent (decision point for movement between conveyors), sensor agent (cooperation and execution), robot and storage area agents (packing and unpacking operations control) and order and product agents (process planning for product customization). Real-time simulation of control agents and behavior visualization of each agent in coordination with other agents are the main characteristics of the proposed simulation tool.

AnyLogic simulation software is one of the well-known tools for creating and developing agent-based, discrete event and system dynamics simulation models concurrently, and is used in this research as well. The use of Java object-oriented programming structures in AnyLogic for agent-based simulation models would enable a real system representation and changes management. In order to find how a system would behave as a whole and find about the individual behaviors of system objects, AnyLogic is a suitable option to model the system from bottom to the up starting from objects (i.e. agents) identification in the system and constructing their behaviors by defining rules for each of them. In this way agents can be modelled to interact with each other and make possible connections with the environment and to share information which would provide an emergent global behavior come out of agent's individual behaviors at the same time.

Defining the possible behaviors of each agent can be accommodated by using state charts and action charts available in the software and using process flowcharts simultaneously while modeling agents provide dynamic strengths in terms of industrial applications. Event- and time-driven behaviors can be explained by constructing state charts featured by different algorithms, transition between states and state changes (Borshchev, 2013a).

## **2.5. Reconfigurable Manufacturing Systems Modelling Techniques**

There are different methods of modelling reconfigurable manufacturing systems such as mathematical, ontologies, petri-nets, object-oriented, discrete-event simulation, system dynamics and agent-based simulation modelling. A method for finding the optimal configurations considering utilization improvements in each of the selected designs has been implemented based on the stochastic model presented by (Xiaobo et al., 2000). A system dynamics simulation model has been considered in (Elmasry et al., 2012) to deal with the scalability problem of the manufacturing system's capacity measurements. Agent-based modelling paradigm in context of manufacturing systems applications comprehensively surveyed and discussed by Monostori et al. (Monostori et al., 2006). Coloured timed object-oriented petri nets modelling technique is utilized by Meng (Meng, 2010) and implemented on a reconfigurable manufacturing system to model reconfigurable processes. Performance measurements of a reconfigurable manufacturing systems has been investigated (Hasan et al., 2012) using a discrete-event simulation method in order to find the optimal production scenario.

## **2.6. Hybrid Simulation Methods for Manufacturing Systems Control**

Hybrid methods were introduced and implemented for the simulation of manufacturing systems such as hybridization of discrete and continuous simulation methodologies presented by Brito et al. (Brito et al., 2011). Generally, Discrete-Event Simulation (DES) has been compared to System Dynamics (SD) simulation through different types of criteria to discover the possibility of integration and hybridization of these two approaches of simulation. Moreover, in (Venkateswaran and Son, 2005) DES and SD simulation combined together to develop simulation of a manufacturing system case study for the improvements on system's behaviour in terms of production rate in



different scenarios. A framework for synchronization of DES and SD simulation paradigms was proposed in another work, where IDEF0 function modelling tool has been used (Helal et al., 2007).

Agent-based Modelling (ABM) is a useful tool in the creation of hybridized simulation models, when there are autonomous agents in the system to deal with complex conditions such as frequent changes. A simulation of Agent-based Systems illustrates the behaviour of each agent in the presence of system disturbances. Opportunities are provided to try different software platforms for Multi Agent-based System modelling for production control purposes (Barbosa and Leitao, 2011).

AnyLogic simulation software is a well-known tool for creating and developing hybridized models consisting of agent-based, discrete event and system dynamics simulation, which is used in this research. The use of Java object-oriented programming structures in AnyLogic for agent-based simulation models would enable a real system representation and changes management. AnyLogic helps acquire system behaviour as a whole and learn about the individual behaviours of system objects. AnyLogic is a suitable option to model the system from bottom to up starting with objects (i.e. agents) identification in the system and constructing their behaviours by defining rules for each of them (Borshchev, 2013b).

## **2.7. Concluding Remarks**

According to the literature survey in the field of capacity and scalability planning for reconfigurable manufacturing systems, it is mainly found that the system dynamics simulation modelling and mathematical programming can function as applicable approaches to identify the optimal level of scalability of manufacturing lines that are producing different number and variety of products and have several changes in their processes. Moreover, different cost indicators are examined in each of these proposed approaches in order to determine the most suitable investment strategy for the capacity planning. Other simulation modelling methods such as discrete-event simulation and agent-based modelling approaches have the potential for using in capacity planning problems for reconfigurable manufacturing systems.

In addition, as it is discussed in the literature, many industries (e.g. Automotive OEMs and suppliers) base their decision in systems' design and processes evaluation on discrete-event simulation. Agent-based simulation can simulate every possible action for each process through state charts, instead of assuming approximate times of different operations. Modelling a reconfigurable manufacturing system using discrete-event simulation integrated with capacity and scalability control functions using communication rules is one of the main contributions of this research which enables recommended capacity for different production periods and illustration of the capacity changes in the results of the simulation scenarios. Determining the required capacity during a single production simulation run using discrete-event simulation is not achieved before which is the gap that is found in literature.

Furthermore of the research on capacity planning for reconfigurable manufacturing systems, there are other manufacturing control techniques introduced in the literature that are useful for controlling associated changes for accommodating different customer product demands into the manufacturing systems which create substantial needs to investigate about them. It can be concluded from the survey in this field of research, the basic reference architecture that have been proposed in 1998 called PROSA would be the basis for design, development and implementation of the rest of the proposed manufacturing control systems based on agents. Since that time, most of the researchers have attempted to develop their own way of control system design and development with the existing tools such as object-oriented programming tools like UML (Unified Modeling Language) based on PROSA reference agent architecture. Moreover, object-oriented programming and modeling tools and techniques for manufacturing systems have played a significant role in holonic agent-based design of production control systems in a way to build a strong framework for defining, designing, developing and controlling of agents in different kinds of manufacturing systems. Also, several software platforms have been developed for multi agent-based system design and simulation through two powerful programming languages, JAVA and C++, which will provide different functions for designing agents (i.e. holons) in manufacturing systems. As a result, it seems illustrating real-life applications and industrialization of agent-based

holonic control systems for manufacturing systems using desired and preferable software platforms and simulation tools was the purpose of research in this area in the recent years.

## **CHAPTER 3: METHODOLOGY AND MODEL DEVELOPMENT**

### **3.1 Introduction**

In this chapter, a new methodology of production capacity and scalability control using discrete-event simulation integrated with machine resources pool capacity control function using communication rules is developed. IDEF0 functional modelling diagram is used in order to illustrate inputs, control, mechanism and output of this approach. As a potential extension of the proposed capacity planning methodology, a framework consisting of the agent-based model of the manufacturing system modules integrated with the discrete-event simulation is presented with the help of agent-based control principles and IDEF0 functional modelling.

### **3.2. Capacity Planning Simulation Methodology**

Developing this new capacity planning approach enables the control for scaling up or scaling down the manufacturing system by using simulation modelling and add or remove the needed number of machines when it is needed. This will help the manufacturer to know according to the maximum defined allowable queue capacity for each workstation and considering that system stop and product flow blockage should not happen, add required number of machines to the system in order to accommodate the customer order arrival rate changes. In the following, the IDEF0 diagram (Figure 5) illustrates the inputs, control, mechanisms and finally outputs of the simulation model for capacity planning in order to better understand development process of this modelling approach.

In this methodology it is necessary to first identify the building blocks (i.e. system modules) of the manufacturing line, manufacturing process plan and sequence of operations. This step identifies the overall structure of the manufacturing system in order to know how many workstations are currently represented as required processes in the manufacturing system that has the significant impact on manufacturing processes of the products. Moreover, the queuing process, transportation of products and routing processes needs to be modeled as they are existing in the real production system. Then,

due to the scope of having scalability in our model, it is needed to find an applicable way to represent storage opportunities for the required number of machines which are needed because of the fluctuations in the demand level (i.e. order arrival rates). The rule model presented in Figure 6, demonstrates the proper way to manage this issue.

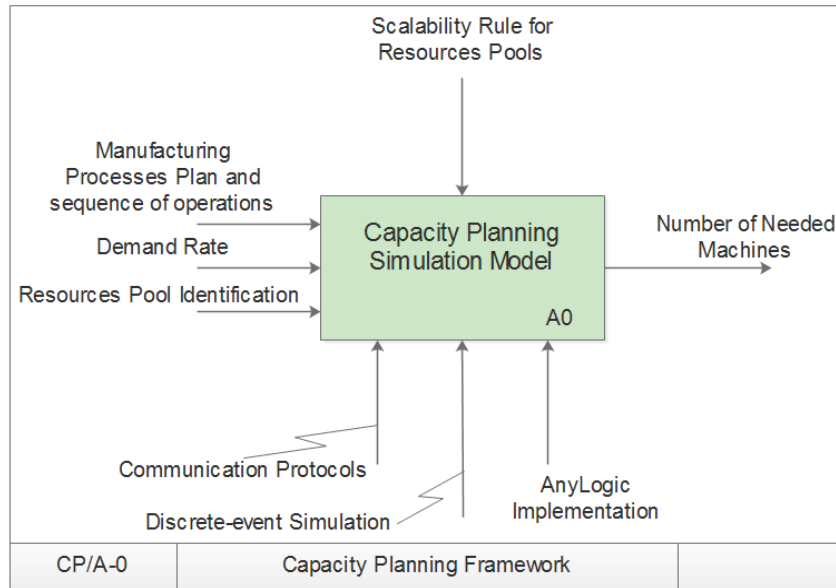


Figure 5. A-0 IDEF0 functional model of capacity planning simulation modelling approach

In this discrete-event simulation model, there is a dynamic variable defined for the number of needed machines during the production processes for different workstations. This variable is changeable and it changes when the queue capacity of the workstation reaches to its defined maximum capacity level according to the order arrival rate (i.e. demand rate) changes to the higher amounts. The simulation model of the system will automatically request for adding the new number of machines in this situation. This defined rule indicates that whenever the new added machines are not needed (i.e. idle), they will be automatically disabled and removed from the system.

In this phase of capacity planning simulation modelling for the reconfigurable manufacturing system, AnyLogic simulation software platform helped the modelling procedure of the aforementioned defined rule. In this simulation model, resources pool function of this software enables modelling the scope of the rule easier. So, for each of the workstations of the manufacturing system that are performing production processes, resources pool functions should be defined. These resources pools include the variable

number of machines that would be needed for the workstations. When the customer demands increase, the amount of the work in process will be increased accordingly and this will lead to increase in the number of queues. When the number of queues for each workstation reaches to its maximum level, the workstation module requests adding of more machines of the same in order to prevent the stop of the manufacturing line and balance the system production flow. In this way, the increased utilization of the current workstation will be shared with one or more other workstation that can function in parallel with the current one.

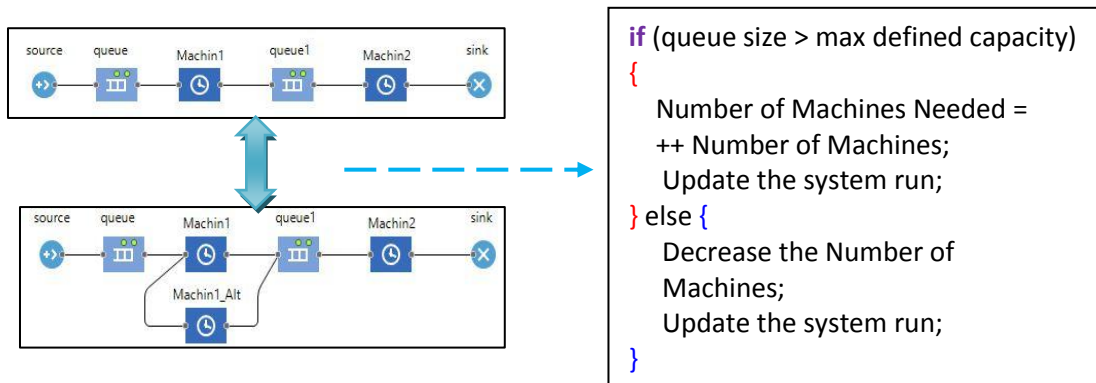


Figure 6. Coding scenario for the system scalability

The communication protocols between different workstation modules and resources pool building blocks are defined by benefiting from AnyLogic software functions. Also, this platform can ease the implementation of the proposed capacity planning simulation model in terms of providing recommended capacity in terms of number of needed machines for a reconfigurable manufacturing system during different production simulation runs. Moreover, this modelling approach is capable of responding to different number of order arrival rates in both deterministic and probabilistic conditions. In these conditions when the demand rate increases, the manufacturing line will not stop working and will just add required number of machines in the system for decreasing the possibility of system blockage and smoothing the flow of the production. In the next chapter, the working procedure of this model is verified and different production scenarios examined with this method. In the next section the potential extension of the current simulation modelling approach into integration with state chart agent models are explained.

### 3.3. Simulation Modelling Framework for Agent-based Integration

In the previous section, the main methodology for the scalability and capacity planning of a reconfigurable manufacturing system is proposed and the benefits of this modelling approach are discussed. In this section, the potential agent-based extension of the proposed discrete-event simulation modelling is presented. In fact, the approach of modelling the distributed control system for a reconfigurable manufacturing system using discrete-event simulation and agent-based modelling is specified. This approach mainly is useful for constructing easy to change agent rules in order to update the function of the defined agents in the system during changes in production and processes which agents will enable to communicate with each other and build the optimal decision base on the system performance requirements such as required production throughput, no blockage, reducing the effect of bottlenecks and so on and so forth. Unfortunately, this modelling approach has the limitation in terms of having the capability for identifying number of needed machines required for different steps of production. It just helps the production planner to find the competitive solution for adding the more flexibility for controlling the manufacturing system functions. The IDEF0 function modelling method used to construct the framework of hybrid agent-based discrete-event simulation modelling. Figure 7 shows the A-0 IDEF0 model of this framework which has inputs that trigger the activity, controls to direct and adjust the activity, mechanisms for activity performance and output to show the results of the that.

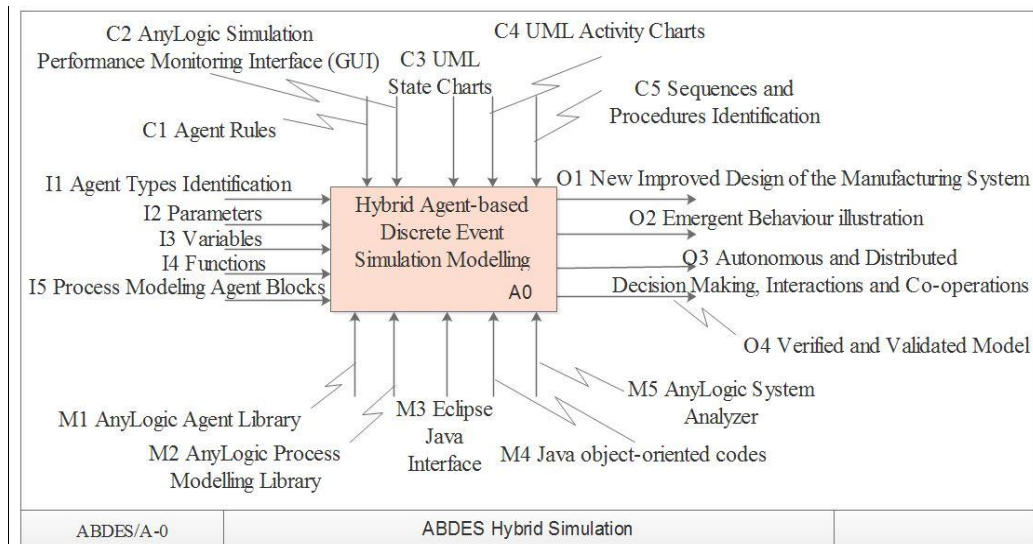


Figure 7. A-0 IDEF0 Functional Model of Hybrid Agent-based Discrete-Event Simulation Modelling

As the Inputs, first, all the required agents types for the manufacturing system need to be defined (I1), second, for each agent necessary parameters (I2) and variables (I3) should be specified which help to identify functions (I4) in the system and make connections between agents, third, process modelling agent blocks should be defined through the AnyLogic process modelling library in order to build the discrete-event simulation model. As the Controls, agent rules (C1) with the help of UML state charts (C3) and UML activity charts (C4) are formulated where java coding structures enables rules definitions. AnyLogic simulation performance modelling interface (GUI) (C2) provides the simulation runs, replications, graphical animations and analysis performance for verification and validation of the simulation model. As the Mechanisms, AnyLogic agents library (M1) helps to perform agent's definitions and build their required rules, AnyLogic process modelling library (M2) performs process modelling agent blocks definitions for the discrete event simulation model, Eclipse java interface (M3) enables the editing of the java object-oriented coding structure (M4) as a tool in order to modify or improve the agent's rules, AnyLogic system analyser (M5) performs different types of system performance analysis in order to provide the opportunity of comparison between different simulation replications and show the variability analysis of different system functions. Finally, the Outputs are the new improved design of the manufacturing system (O1), illustration of the emergent behaviour (O2), autonomous and distributed decision making, interactions and co-operations (O3) and a verified and validated simulation model (O4).

In this proposed framework the following steps need to be taken into consideration for the successful implementation of the approach;

1. Analyze the product assembly structure and the possible product variants
2. Analyze current production system and control structure
3. Identify Agents, based on the system modules and functions
4. Develop state charts for each module to model their behaviours and logic rules
5. Develop if-then-else rules and algorithms for required elements of state chart



6. Construct the discrete-event simulation model to connect different building blocks of the system and create production scenarios
7. Make comparisons between different scenarios and the results
8. Analyze the change capability of the system

### **3.4. iFactory**

The case study considered for this research is based on the Transformable Production Platform (iFactory) available in the Intelligent Manufacturing System Center at the University of Windsor. This assembly system is changeable in terms of system layout and functionality which enable the reconfiguration of the production system easily and reliably. This system is capable of having several modules for assembly and inspection processes. Furthermore, the technology, control, interfaces and modularity concept that are utilized in this manufacturing system are important enablers for changeable and reconfigurable processes and production plans capable of producing variety of products. The purpose of illustrating this new platform for manufacturing is to understand the new manufacturing system design paradigms in the lab environment and conduct several research projects to initiate and develop real-life industrial applications of this system.

The very first design of this learning factory system was initiated and developed by collaboration between University of Stuttgart in Germany and Festo Automation. The similar reconfigurable production system located in IMS Center at University of Windsor also was developed with collaboration of Festo Didactic for execution. This system includes changeable manufacturing units such as conveyors, different assembly and inspection stations and an automated storage and retrieval system as well. The system is featured by quick structure and layout changes and capable of having different functional system configurations enabled by various branches, connectors, and termination conveyor units executed by advising from reconfigurable logic controls and standardized mechanical and electrical interfaces. The flow of materials in the assembly system are handled on the upper level transports work pieces on platforms forward and the lower level transport empty pallets backwards (ElMaraghy et al., 2012). The following image (Figure 8) demonstrates the iFactory with the different kinds of system modules consist

of: 1) AS/RS module for storage of plate parts and completed products, 2) vision quality control module for monitoring the quality criteria defined for the system, 3) robotic assembly module for the assembly of cups, 4) manual assembly module for assembly of gauges and, 5) conveyor transportation module for transferring between different stages of desk set production.

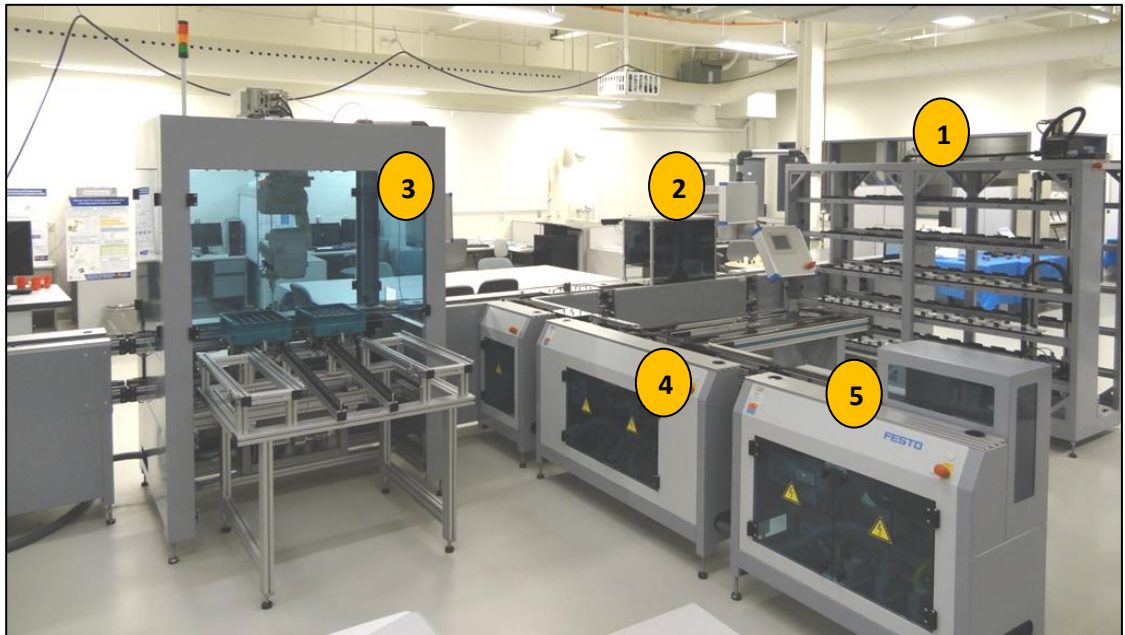


Figure 8. iFactory Intelligent Flexible Assembly System [Located at the Intelligent Manufacturing System Center (IMSC) at the University of Windsor]

### 3.5. iFactory Capacity Planning Simulation Model Development

In the simulation modelling framework using agent integration, the main model is based on discrete-event simulation which different current existing building blocks of the manufacturing system can be easily modeled considering process modelling concept available in AnyLogic software platform and each of these building blocks can be considered as a system module represents by state chart in order to model the possible behaviours that can happen for the manufacturing module. These state charts can help the manufacturing system to update the status of each its modules according to the possible system changes that may happen in the future. For example, if the robot station experiences a high demand of products and more than defined accumulated queue, the identified if-then-else rules with the help of state chart can help this station to share the

requested extra utilization with the manual assembly station to assemble the cups manually and prevent the stop of workstation and blockage in the flow of the products. Also, this approach has the capability of message transmission between different modules of the system in order to create a production protocol to reach to the desired production output and cycle time.

The main limitation of this simulation modelling approach is, the simulation model of the manufacturing system is not capable of automatically increase or decrease the scale of the system in order to add parallel workstations to the bottleneck modules for preventing long queues and system stop. This means, by developing this new approach for scalability and capacity planning as shown in Figure 9, there are resources pools that are introduced into the current discrete-event simulation model, for example for several assembly and quality control stations in a manufacturing system, which their function is to provide the number of needed machines when the queue capacity reaches to its highest level and when the production flow reaches to a smooth level that there will not be any need to have more machines of that kind, the extra machine will go back to the resources pool in order to serve the later order arrivals of the customer.

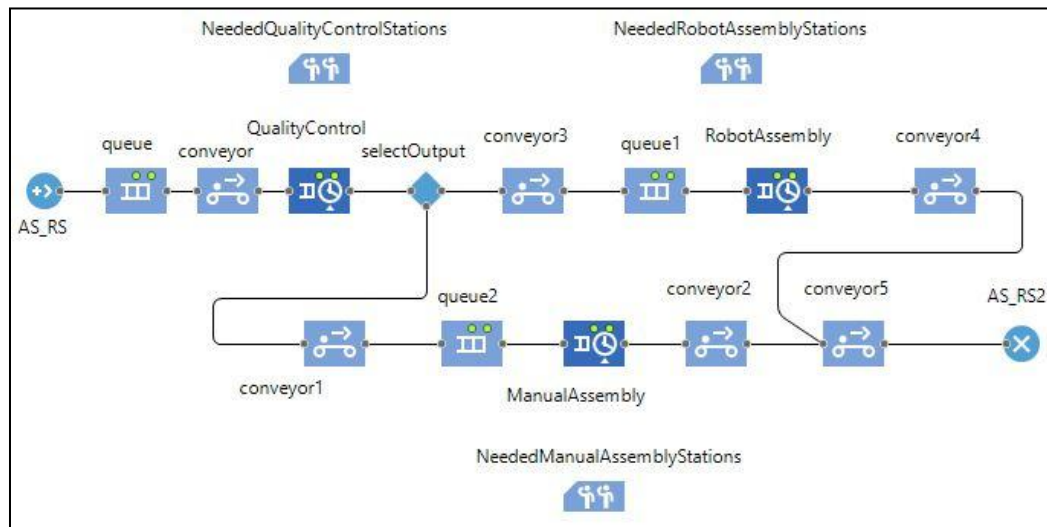


Figure 9. Capacity Planning Simulation Model

This capacity planning model enables the reconfigurable manufacturing system to automatically change the scale of the manufacturing line in order to respond to the demand changes. In the presented discrete-event simulation model that it is used for the

iFactory case study, it starts and ends with AS/RS system module which the customer orders will be started to be produced from this point and when the orders are completely manufactured, it will be returned to the AS/RS system again for the storage purpose. In the discrete-event simulation model, they are represented as source and sink of the model. In the source of the system, the manufacturer is able to increase or decrease the demand level as the input of the system and investigate the effect of these changes on the output of the system which is the number of needed machines for each workstation. In this discrete-event simulation, there are vision quality control, robotic assembly and manual assembly workstations as the main processes of the iFactory system. Each of these stations has the processing time which has to be spent in order the work in process products can move to the next required processes. Also, as it is shown in the simulation model the required number of queues and conveyors are modeled as exactly these processes happen in the real iFactory system.

The discrete-event simulation model of the iFactory will be completed with the use of these processes. Resources pool capacity control functions need to be designed for the machines that are processing assembly of the products, in order to illustrate the scalability process of this reconfigurable manufacturing system. Each of these resource pools in the simulation model consists of variable number of machines for each quality control, robotic assembly and manual assembly stations. As it was presented in the methodology chapter, there is a communication protocol between the workstation and the machines resource pool that whenever the number of work in processes (i.e. queue capacity) reaches to its maximum defined level by the iFactory system, the workstation request for the adding of a new machine in parallel work of the current one. Moreover, if the customer demand defined in the sink module option (i.e. AS/RS) increase to the higher levels, the workstation is able to request for adding of the more machines in parallel work of the current ones. With the defined rule of Variable Capacity Level Of Resource Pool – Needed Number Of Workstations.idle() the manufacturing system is able to remove the idle workstations when the work in process demand levels are reduced to a lower level. This rule permits that whenever increase of capacity is needed, the required machines will be added, and whenever the increase capacity is not needed, the added machines will be automatically removed.

These identified resources pool for the discrete-event model can be used for the other building blocks of the manufacturing system such as inventory system or even conveyors that whenever each of these modules reaches to its maximum defined capacity level, the required number of extra modules add to the system for preventing the system blockage especially when the module of the system, functions as the bottleneck of the manufacturing processes with the highest processing time, so the required number of modules will be added according to the defined rules. With this simulation model, the manufacturers can benefit a lot in terms of knowing exactly when they have to add machines and exactly at what time they have to remove the machines that are not required. This way, they can plan very carefully over the different shifts of production in their company, how many machines they have to plan to use on average to reduce the possibility of system obstruction during different periods of production. The following table shows the processes and sequence of operations for producing the desk set product (Table 1).

Table1. Processing plan and sequence of operations

<b>Sequence</b>	<b>Operation</b>	<b>Processing Time (seconds)</b>	<b>Maximum queue capacity</b>
1	Processing order from AS/RS	8	-
2	Transporting to vision quality control station	4	-
3	Processing in vision quality control station	4	2
4	Transporting to robotic assembly station	6	-
5	Assembly of the cups	23	3
6	Transporting to AS/RS	11	-
7	Processing in quality control station	3	-
8	Transporting to Manual Assembly station	7	-
9	Assembly of gauge	5	2
10	Transporting to AS/RS for inventory	8	-

For more clarification of how the model is working, the inputs of the model are demand rate, maximum queue capacity level, processing time and sequence of operations

which these are the parameters of the model. Also, the variable of this model is the required number of machines where changes according to the defined scalability rule. The output of this model is the recommended capacity for number of needed machines during different production periods. This simulation model is capable of determining number of produced products in each time (i.e. throughput), utilization rate of each machine and processing modules, and number of work in process products.

In the next chapter, both deterministic and probabilistic arrival rates are examined in order to monitor the behaviour of the number of needed machines during the time for each of the workstations and examine the chaotic behaviour of this process.

### **3.6. iFactory Simulation Model Development Using Agents**

In the developed hybridized model of iFactory, two different approaches of simulation modelling, discrete-event (macro level simulation) and agent-based (micro level simulation), are utilized. iFactory deals with different types of processes such as robotic assembly, manual assembly and machine-vision quality control. Therefore, there is a need to use discrete-event simulation in order to define sequences of operations, order arrivals, queuing, events times and system utilization. On the other hand, in iFactory, each of the mentioned modules has its own specific behaviour which can be defined by constructing a state chart. These state charts are the starting point for controlling and examining different changes and disturbances inside the system using agent technology. Accordingly, using each of these approaches separately can limit the scope of controlling and improving the performance of the changeable system effectively. The proposed modelling framework for the changeable iFactory is hybridized discrete-event and agent-based simulation/ modelling methodology which is presented in Figure 10 and shows agent functions, logic flow between agents and where discrete-event simulation comes in. This framework is useful for optimizing the performance of a reconfigurable manufacturing system. Modelling the iFactory using the new hybrid framework requires different types of agents with different specifications to be defined with the help of AnyLogic software. These agents are different because of the different ways they are representing different functional modules of the manufacturing system. For each agent in iFactory, inputs, outputs and behaviour logic rules are identified as following:

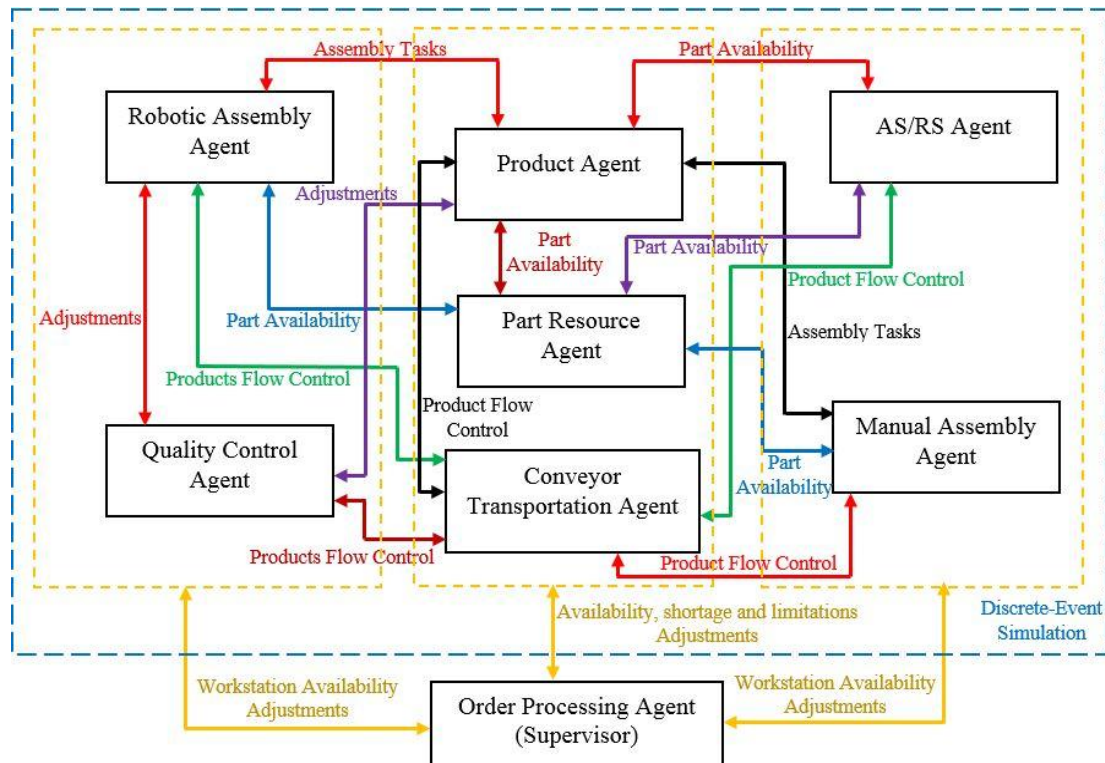


Figure 10. Logic rule between different system modules

**AS/RS Agent:** Inputs are the initial customer's orders created by order processing agent as the first part and completed products as the second part. Outputs are base parts movement handling to be located on the production line for the first part and completed products storage handling when the orders are completed. Behaviour logic rules are, first, changing the state of AS/RS agent from idle (waiting) to working (movements) for products storage handling and vice versa, second, checking the availability of base parts as well as completed products storage, if there is shortage in any of them, AS/RS agent can be replaced by a new one or the new agent can be added in parallel with the existing one to function (Figure 11).

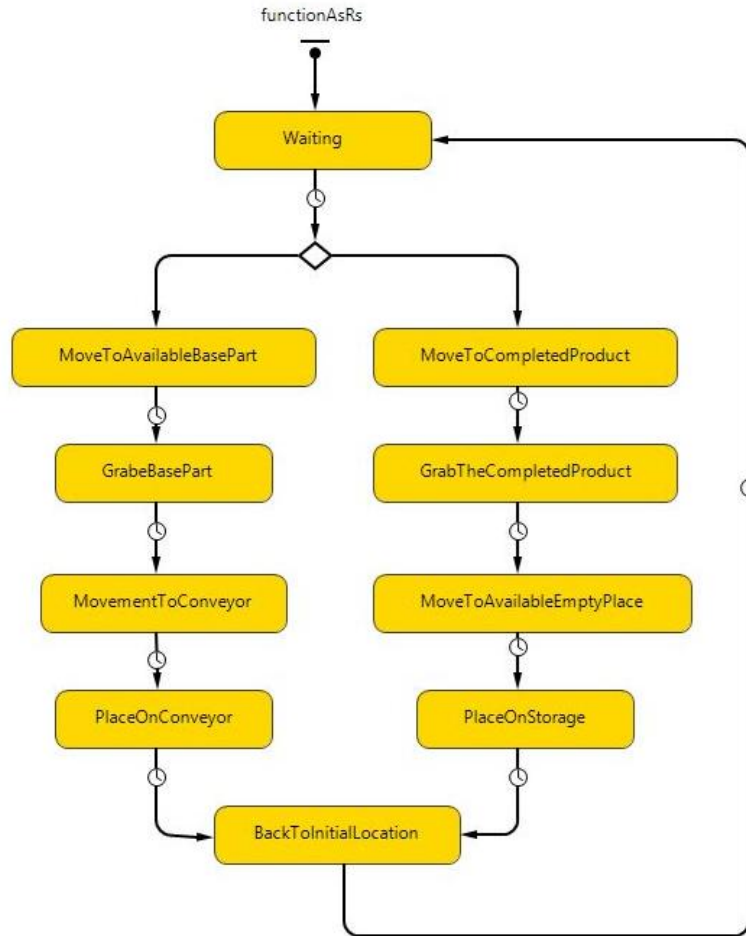


Figure 11. AS/RS Agent Model

**Robot Assembler Agent:** Inputs are the work-in-process products that need short and long cups to be assembled by robotic assembly agent in three different locations as shown in Figure 18. Outputs are finished or semi-finished assembled Desk Set products according to the customized customer's order. The behaviour logic rules are, first, the defined state chart for robotic assembly agent which is illustrated in Figure 12, shows robot state changes in terms of movements for grabbing different types of short and long cups and assembly of them considering the customer's need for having any of them, second, in case of robotic assembly agent failure, it can be replaced with the new one up on the request from order processing agent, third, if there are shortages in any type of cups availability, part resources agent should be informed about that in order to mend the problem and provide the required parts.



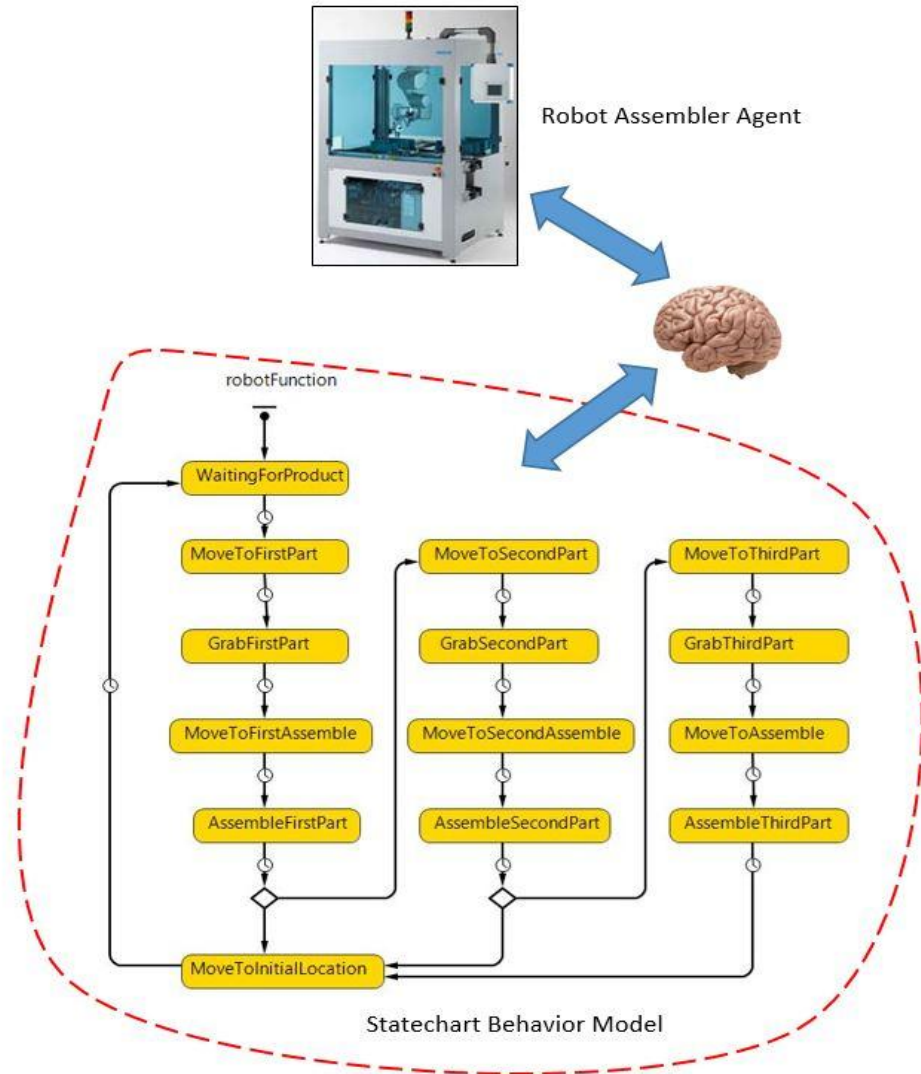


Figure 12. Robot Assembler Agent Model

**Manual Assembler Agent:** Inputs are the work-in-process Desk Set products which need different types of gauges parts to be assembled on them according to customized customer’s orders in three different possible locations as shown in figure 20. Outputs are finalized assembled Desk Set products. The behaviour logic rules are, first, gauges parts availability should be confirmed by the operator through the available user interface and in case of shortages in any type, part resources agent will be informed to provide the required parts, second, if manual assembly agent faces malfunction of conveyors or switches, it can be replaced by the new one without disruption of other operations (Figure 13).

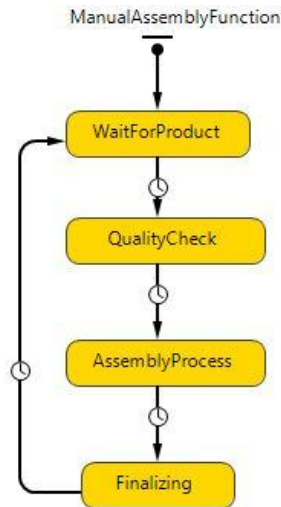


Figure 13. Manual Assembler Agent Model

**Quality Control Agent:** Inputs are finished or semi-finished Desk Set products which require to be checked by the vision system in order to be confirmed for quality and ready for next processes. Outputs are quality confirmed Desk Set products in different stages of production. Behaviour logic rules are, first, make sure that cups and gauges assembled on the base part accurately and match to what the customers ordered, second, in case of vision system failure, this agent can be replaced by the new one through making a request to order processing agent (Figure 14).

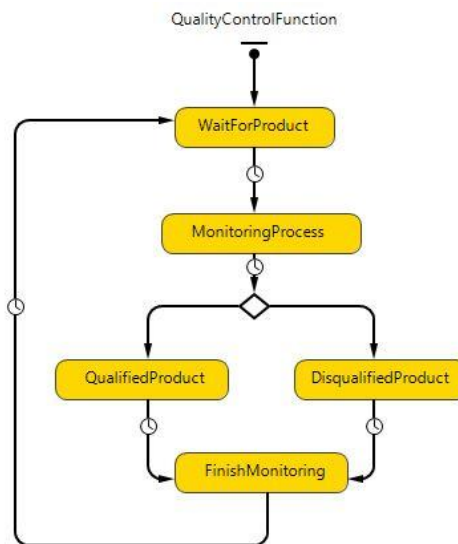


Figure 14. Quality Control Agent Model

**Product Agent:** Inputs are required processes which are needed to be performed for having a complete assembled Desk Set product. Outputs are finished Desk Set products that complete all the required production operations identified by order processing agent. Behaviour logic rules are, first, find about the availability of the required workstations that should do operations on the product as well as the part resources, second, control the routings of the product during production procedure by collaborating with conveyor transportation agent and order processing agent in order to decrease the time that the products stay in the system as well as the quantity of work-in-process products (Figure 15).

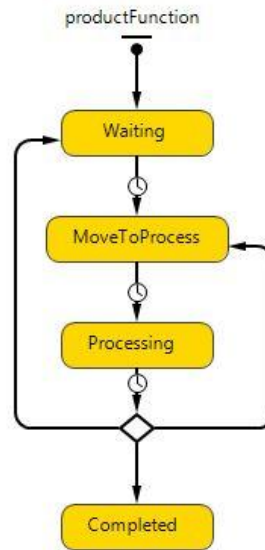


Figure 15. Product Agent Model

**Part Resources Agent:** Inputs are the Desk Set product's orders created by order processing agent that need different types of cups and gauges parts to be assembled on them. Outputs are provided required parts for the robotic assembly, manual assembly and AS/RS agents in order to enable them to complete their operations. Behaviour logic rules are checking the parts availability in the mentioned agents and in case of shortages provide the necessary parts with collaboration of order processing agent (Figure 16).

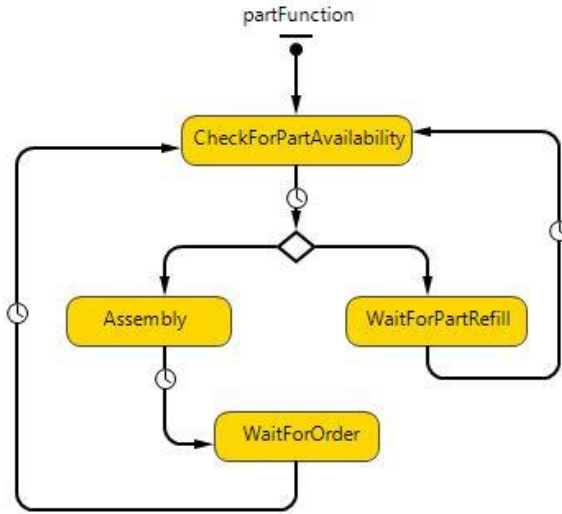


Figure 16. Part Resources Agent Model

**Conveyor Transportation Agent:** Inputs are Desk Set products in different stages of production which require transportation between workstation agents. Outputs are transportation functions which are provided for the product agent. Behaviour logic rules are making sure the product agents transport to right places by checking with order processing agent all the time and confirming that all the required conveyors are functioning which in the case of failure they need to be replaced (Figure 17).

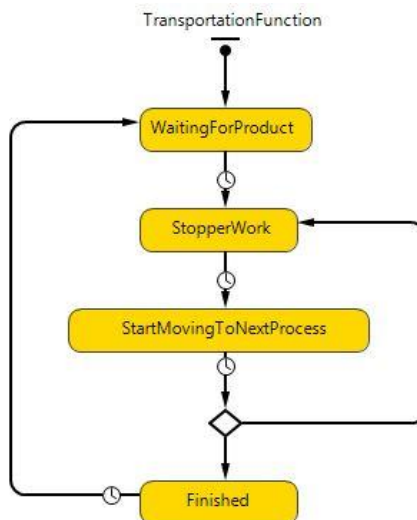


Figure 17. Transportation Agent Model

**Order Processing Agent:** Inputs are all the information collected from workstations, part resources, conveyors transportation and product agents. Outputs are given directions and instructions to all the agent in order to make sure they can be functioning as required to produce the customized ordered products. Behaviour logic rules are, first, confirm with all the required agents for producing the ordered products that they can do the required operations, second, provide feedbacks to agents in order to manage possible disturbances like failures and shortages. This agent can be mentioned as supervisor agent in iFactory model.

**Main Processing Agent (Discrete-Event Simulation):** This agent is defined according to the requirements for hybridized modelling completion in AnyLogic software. In fact, the process modelling of the iFactory for the Desk Set production using AnyLogic process modelling library is constructed in this agent as shown in Figure 19. Constructing this agent is one of the important steps of the hybridized simulation modelling which is presented by discrete event simulation modelling principles in AnyLogic platform. These principles consist of identifying input and output of the system which is identified by Source and Sink object functions.

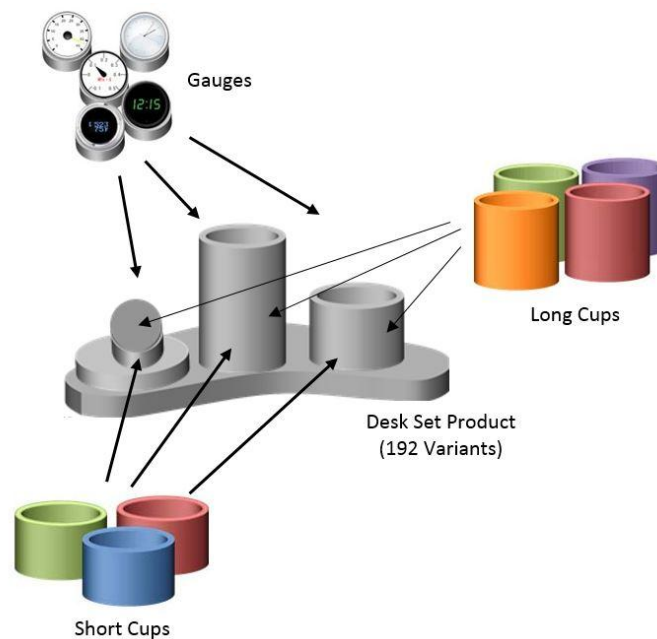


Figure 18. Desk Set product variants and structure (ElMaraghy et al., 2013)

These functions enable us to control and compare the amount of orders inputted into the system and amount of completed products we are getting from the system considering the timeline. Moreover, several queues are needed to be considered between different operations of the manufacturing system which is always occurring in the real-life and the capacity and inter-arrival time should be defined for each queue. Delays and Services object functions are considered as the processing time of the operation depends on the nature of the production flow and transportation. In addition, several conveyor object functions can be used in the system for the matter of products movements, in different completion procedures, to the next required production steps. Depending on the required operations for a product, there are different routings in the system which needs managing by Select Output object functions. This function will create a conditional requirement for a product to enter from which available rout in order to continue the required production processes.

Figure 19 shows the current existing layout of the iFactory discrete event simulation model for processes modelling which starts with the AS/RS with the rate of 5 orders per minute coming to the system, push forward the platform part to the first operation which is quality control work station through the conveyor. The processing time for this workstation is 4 seconds on average. Sequentially, the product is directed into two different routes with the probability of %50 to enter from route 1 for the robot assembly operation or enter from the route 2 for the manual assembly operation. This condition examines whether the product needs cups to be assembled or gauges. The processing time for robot station is on average 33 seconds and for the manual assembly is on average 11 seconds. Afterwards, all the completed products are routed into AS/RS at the final stage for the storage. As discussed, each of these blocks is represented by an agent which models the behaviour of each module with the specified conditions, algorithms and rules in order to satisfy the changeable environment for the iFactory. This experiment has been done on iFactory at the same time with the AnyLogic simulated model of the exact created conditions for the experiment and it is founded that normal behaviours of agents hybridized with the discrete-event simulation model are functioning the same way as the behaviours and output of the iFactory in real-life. Therefore, the hybridized simulation model is verified to be the correct representation of real-life.

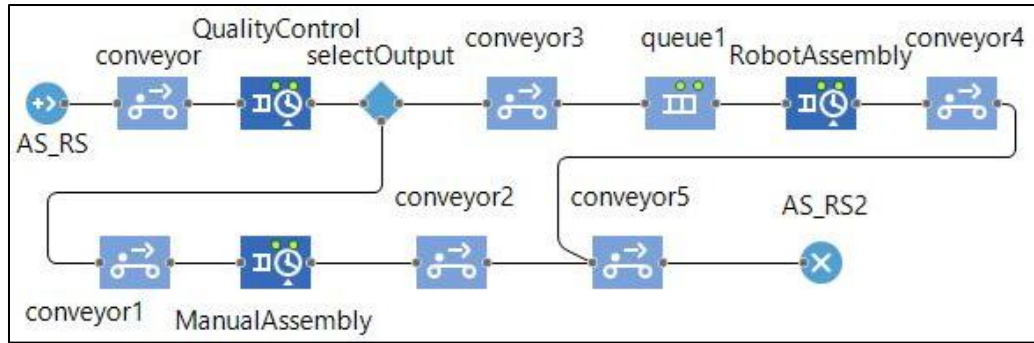


Figure 19. iFactory Model for Discrete-Event Simulation

To examine the emergent behaviour of the proposed hybridized manufacturing system modelling framework, different production scenarios can be simulated and validated. For instance, as it is understood from the preliminary simulation model that the robot assembly station represents the bottleneck of the system because it is accumulated highest number of queue and it is the most used workstation because of the customer's demands to have cups in their products instead of gauges. Accordingly, this station is considered as the blockage of the production flow because it will affect all the other processes completion if the defined queue exceeds its defined capacity. In this situation, another robot assembler workstation can be added to the system in parallel with the existing one to accelerate the production. This scenario illustrates the system's intelligence according to the if-then-else rules defined for the robot agent capabilities and automatic insertion of different types of agents when the production system is constrained at certain points of production processes. Also, a scenario includes the discrete-event simulation model only and discrete-event simulation including robot agent is investigated in the next chapter to show the possible effectiveness of the proposed approach using state charts and agent rules.

## **CHAPTER 4: EXPERIMENTAL RESULTS AND DISCUSSION**

### **4.1. Introduction**

In this chapter, several simulation modelling scenarios of the iFactory system are presented. First, the capacity planning discrete-event simulation modelling methodology that is presented in the previous chapter is examined using AnyLogic software. This scenario includes two main sections which the first section is the discrete-event simulation only scenario consists of simulating different type of events that are occurring in the iFactory. It first starts with AS/RS as the inventory of the desk set base part and it will go through the next required processes for the product variant such as cups assembly, gauges assembly and quality control workstation. The results are presented for a scenario when customers order 5 products per 60 seconds on average. In the second section, the resources pools function and communication rules for scalability are integrated into the design of the discrete-event simulation model in order to solve the blockage problem caused by the robotic assembly workstation in the first simulation scenario. The impact of adding these resources pool into the model is investigated by using deterministic (i.e. 5, 10 and 15 orders per minute) and probabilistic (Triangular (5, 10, 15)) order arrival rates in simulation scenarios and the behaviour of the scalability process is examined through simulation results.

The potential improvement opportunities of the capacity planning simulation model for the iFactory are discussed in terms of development of state chart agent model for the robotic assembly module instead of the robot assembly event in the discrete event simulation model in order to find the other potential solution for the blockage problems that were existed for the discrete-event simulation only scenario. The result of this possible improvement in the simulation model can be compared with the main results that it is found in the capacity planning simulation model. Furthermore into these comparisons, the industrial benefits and significance of the capacity planning methodology and scalability results for the reconfigurable manufacturing systems are discussed in the final section.



## 4.2. Simulation Scenario Using DES Only

The following model (Figure 20) shows discrete-event simulation of the iFactory system. The assumptions consist of 5 product orders (i.e. demands) on average that will be received by the AS/RS system every 60 seconds which is the starting point of the model and the clock of this model is set to zero in order to run the model and observe the results of the simulation for first 3600 seconds (1hour) as an example.

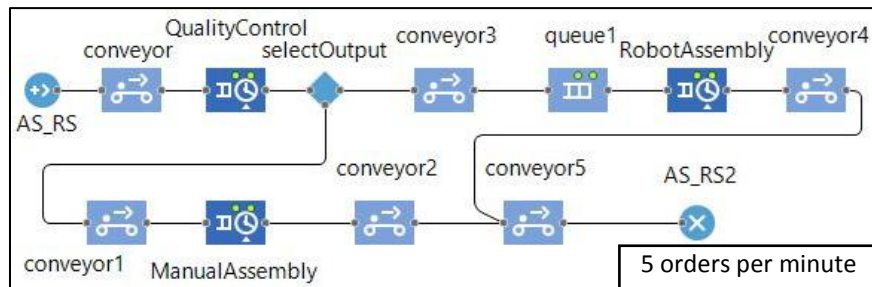


Figure 20. Discrete-event simulation only production scenario for iFactory

The main results of this production scenario after running the model is that, the queue of products accumulated before the robot station, causes the system to become fully loaded which leads to stop of the system. Also, utilization of the robot station is at its maximum level and cannot function in a flexible way to decide about the control process of the problem. The iFactory encountered the exact same problem when run using the same production scenario. This problem occurs because the robot station has the highest processing time and after the queue of this workstation reaches to its defined maximum capacity level, it will affect the processing of the other workstations and leads to a stop of the system. Secondary results are that, work in process (WIP) occurs during the high demand, long queues and system blockage exist exactly as real iFactory, and high travel time of products can be effectively decreased by providing the needed capacity requirement for different workstation modules of the system. In the next section, the capacity planning simulation model scenarios are presented which provide a solution for the problem that found in the DES only scenario. Also, changes in order arrival rates for the new model are examined and the simulation results are discussed.

### 4.3. Simulation Scenarios for iFactory Capacity Planning

One of the limitations of the DES only simulation model is that, the model is not capable of identifying the required number of machines for each of the robotic assembly, vision quality control and manual assembly stations during the production run with the simulation model. This means that DES only model is not capable of changing the scale of the system during the single simulation run. There has to be several DES models created to investigate the required number of machines in each configuration of the manufacturing system considering smooth flow of production. The new capacity planning simulation modelling method for a reconfigurable manufacturing system (i.e. iFactory) is illustrated in Figure 21. This model enables the discrete-event simulation of the system to determine automatically the number of required workstations according to the identified resources pool and communication rules for each of the work stations. There is variable number of work stations identified for each of the resources pools considering queue capacity constraints in the following simulation scenario. The defined rule for each workstation and the related resource pool indicate that when the queue capacity level reaches to the maximum number defined by user according to observations in the manufacturing system, each workstation requests its corresponding resource pool to add more machines to the manufacturing system as required.

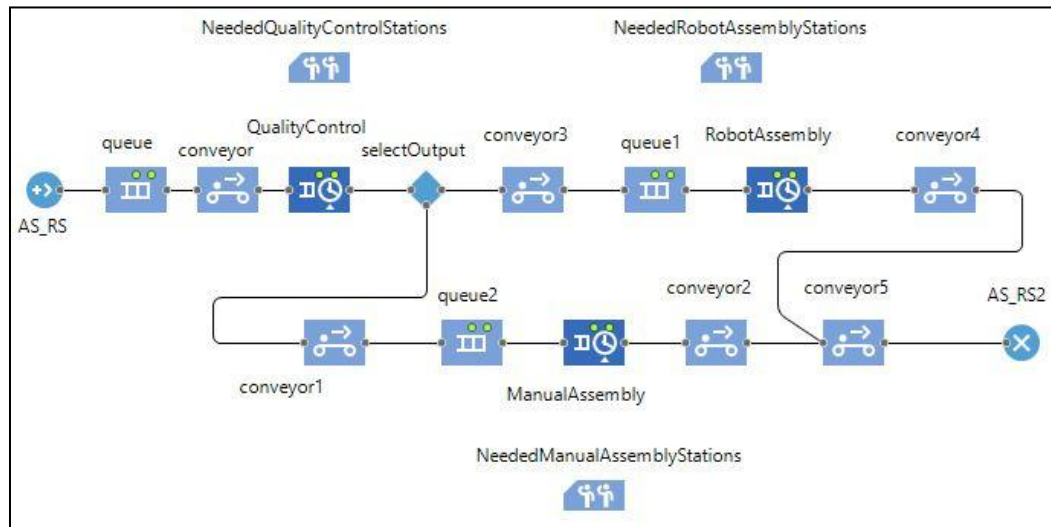


Figure 21. iFactory capacity planning simulation scenario

This simulation model is capable of accepting different rate of demands (i.e. order arrivals) both on deterministic and probabilistic levels. Three different order arrival rates are examined in this model for the deterministic case which is arrival rates for 5, 10 and 15 order arrivals per minute (60 seconds). As it is shown in the below results of the AnyLogic software simulation (Figure 22-24), the number of needed machines for the first 700 seconds of different order arrivals as an example can be determined easily by the manufacturer through reading the numbers that are presented in the following results. Also, in each of these diagrams, the maximum and minimum required number of workstations can be identified. For example, for the arrival rates of five orders per minute, the number of needed robot stations will be reached to its highest level in comparison with the other periods between 250 and 300 seconds as well as 630 and 650 seconds. Moreover, different simulation results are compared with each other and indicate that, the behaviour of the number of needed machines are changed which is one of the good indicators that show the simulation model respond to changes of the arrival rates when it is needed and quickly. In addition, as it is shown in the results for the deterministic order arrival rates, the illustrated behaviour is not represented as a pattern and same oscillation during production periods which is an applicable indication of chaotic behaviour in the simulation results.

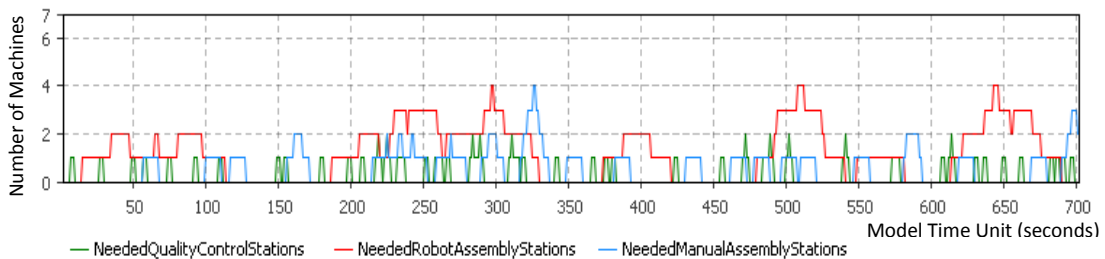


Figure 22. Case study ‘A’ capacity planning simulation results for 5 orders per minute arrival rate

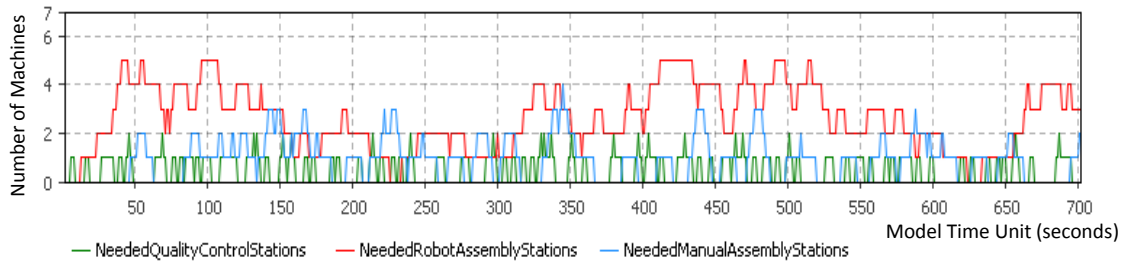


Figure 23. Case study ‘A’ capacity planning simulation results for 10 orders per minute arrival rate

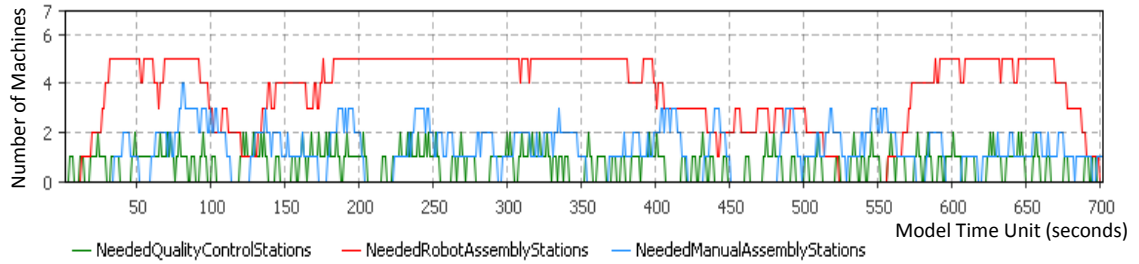


Figure 24. Case study ‘A’ capacity planning simulation results for 15 orders per minute arrival rate

In order to check whether the proposed simulation model can be run with probabilistic order arrival rate, the triangular distribution function with the minimum rate of 5 and maximum rate of 15 orders per minute is examined as for the input of the simulation model. This distribution function is useful when we have an idea about the range of the order arrival rates for the system but there has to be a guess for the average value which in this model is considered as 10. When the simulation model is run with this probabilistic arrival rate, it is found that the system responded to the change as shown in Figure 25. Moreover, the chaotic behaviour of the simulation results can be realized which does not have pattern behaviour. The chaotic behaviour of this probabilistic scenario is also less than the deterministic order arrival rates production scenarios because it is not fixed rate and it is changing from 5 to 15 during the time of production.

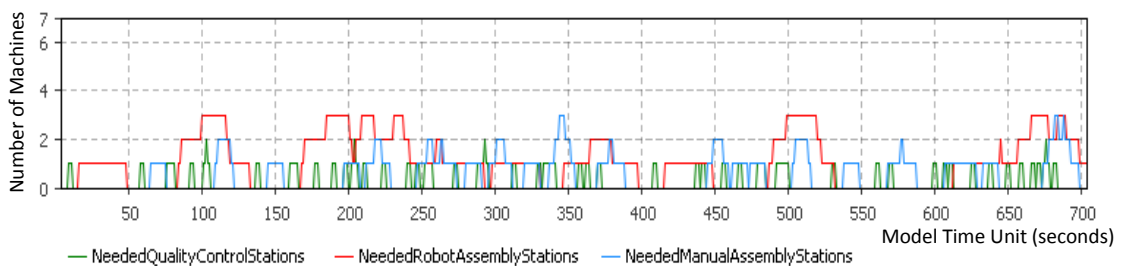


Figure 25. Case study ‘A’ capacity planning simulation results for probabilistic arrival rate

#### 4.4. Potential Extension of the Simulation Model

As it was demonstrated in the DES only simulation scenario, the robot assembly station could not handle the variation of the ongoing demands into the system and create lots of waiting time which is one type of the wasted time for the work in process products and has more impact on increasing the system cycle time. Also, in this process, the

manufacturing line is not balanced because the manual assembly station has the lowest utilization rate among the other workstations and the robot station has the highest one. This problem can be resolved using the identified agent rules through state chart model for the robot station. As it is illustrated in the below Figure 26, first the robot should wait for the product in order to assemble the two cups but before changing its status to the next defined state in the algorithm, it has to check a possible conditional code statement (i.e. if-then-else rule) whether first type of the cup part is available in the storage of the system or not. If the answer to this question is yes, the assembly process will be assigned for the robot station and it will start the assembly of the cup, but if the answer to the question is no, the robot decides to pass the assembly process to the manual assembly module that the cups can be assembled manually by a human operator. In this way the utilization of the robot agent can be effectively reduced because it can share its function with the manual assembly station.

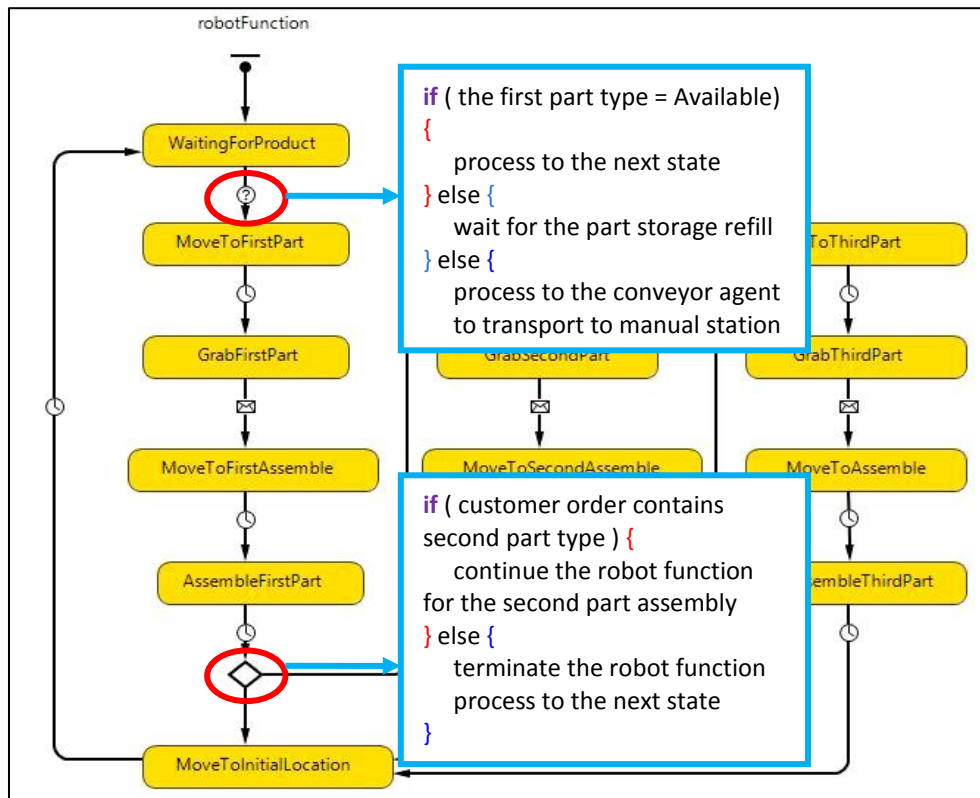


Figure 26. Example of potential agent rules for robotic assembly station

Also, as an example for the second possible rule in the process of cups assembly with the robotic assembly station, after the robot finished the assembly of the first type of cup that is requested by the customer, there is another possible conditional rule that can check whether the customer order contains the second cup part type or not, if the answer to this question is yes, the robot will receive a message to assemble the next cup part type, if not, the further robot assembly process function will be terminated and it will change its state to wait for the next coming work in process products that needs cups to be assembled on them. The following model (Figure 27) shows the possible simulation scenario of the discrete-event simulation integrated with robot agent.

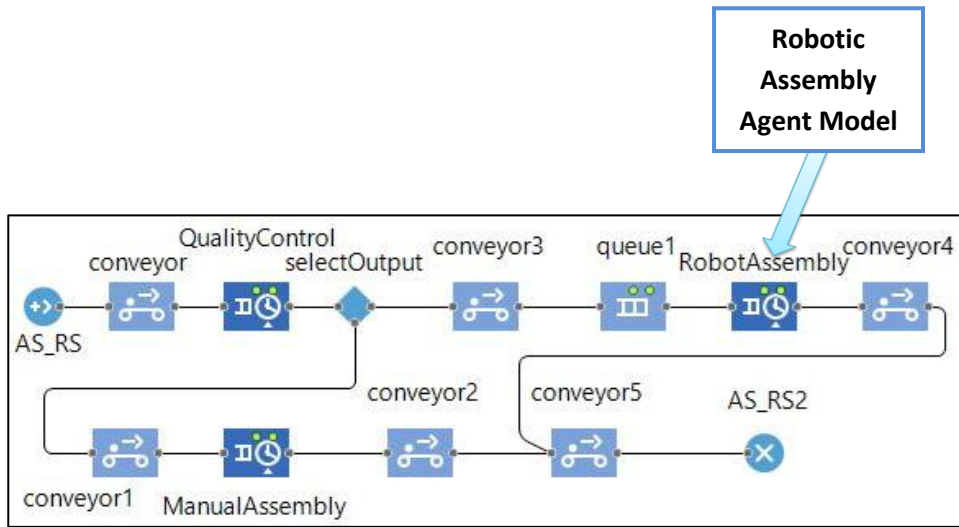


Figure 27. Discrete-event simulation scenario with the embedded robot agent

This simulation scenario can be run for different conditions of order arrival rates as presented in the previous simulation scenario during different several periods of production time. The simulation results of this potential model can be compared with the simulation results that were achieved during the capacity planning simulation scenario.

#### 4.5. Discussion

Today's manufacturing industries encounter several challenges in terms of finding the most suitable and cost-effective solutions for balancing the manufacturing lines and creating a smoother production flow. In the current flexible manufacturing systems that are mainly used in the manufacturing sectors such as automotive industry, there are

different uncertainties such as customer demand levels during different periods of time, stability of production processes, breakdown rate of different workstations or machines in the production line, different schedules of the finished products delivery rate which can create other problems in terms of long queues of work in process products, system blockage, high resources utilization rates, increase in cost of production, etc. The main idea behind designing reconfigurable manufacturing systems is to tackle most of the mentioned problems in the way to enable the modular design of the manufacturing system that manufacturers can easily change the configuration of the workstations in order to deal with variety of product structure changes and demand levels in the meanwhile of the production without stopping the system completely. Moreover, reconfigurable manufacturing systems can provide different alternatives for production planning and control of the production processes that can reduce the cost of the production in comparison with flexible and dedicated manufacturing lines.

Besides the advantages of reconfigurable manufacturing systems, there is problem to control production in terms of capacity and scalability planning, queuing control in different stages of production, required production sequences for each product variant, etc. This means that the centralized control of reconfigurable manufacturing systems still create several problems such as adapting to changes associated with different demand types and arrival rates. Also, the reconfiguration process on the operational level cannot be completed easily and the system is not able to change its scale (i.e. add, remove or modify the machines) when facing long queues of work in process products which leads uneven flow of production and this creates increase in cycle time, travel time, unbalanced level of bottleneck workstations utilization rate and work in process level.

iFactory, is the real-life case study used and an example of a reconfigurable manufacturing system that the presented simulation modelling frameworks, results and analysis are based on this manufacturing system. The problem found in this system is that, the robot station acting as the bottleneck of this manufacturing system has the highest processing time and this will not allow the other work in process products to be assembled by the robot station to be processed quickly and will create blockage in the manufacturing line. With the help of discrete-event simulation available in AnyLogic

software, it is verified that after certain amount of production time, the model gives an error indicating that the production line is fully loaded and cannot process any more new orders with the defined demand arrival rate.

In the discrete-event simulation model for capacity planning of a reconfigurable manufacturing system the uncertainty is considered for the customer demands arrival rate. Since customers have different time to order a product and it is not clear for a manufacturing system how to accommodate this change in number of orders, this lead to an uncertainty that a manufacturer has to deal with. The use of simulation modelling technique helped in simulating this uncertainty and measures the impact of different level of changes in order arrival rates, whether deterministic or probabilistic, on the output of this model which is the number of needed machines. In fact, by changing the order of arrival in the simulation model, it would be easy to determine the number of needed machines for different cycles of production. Moreover, overcoming the uncertainty of the physical implementation after knowing the number of needed machines could be important to investigate, but this research is not dealing with the physical implementation of changing the scale of a manufacturing system to observe the possible consequences.

The limitation of the current manufacturing industries is that if the order arrival rate increases to a higher level, there will be a need for adding more machines of the same type when it is required. The proposed capacity planning simulation approach provides the resources pool functions for each of the necessary workstations and they have the rules indicating that whenever any of these workstations reaches to its maximum level of queue capacity, the machines can be added into the manufacturing line in order to accommodate the increased demand level. These added machines can be removed from the manufacturing system when they are not needed and will return back to the resources pool. This simulation modelling approach provides substantial benefits for manufacturers to control the smooth flow of their production line and according to the simulation results exactly know the maximum required number of machines should be added to the production system and when they have to be disabled. Moreover, with this model, they can insure that their production system will not face stop or blockage anymore.



In the discrete-event simulation model of iFactory as a reconfigurable manufacturing system, the maximum number of queues for each workstation is defined manually which is based on assumptions that can be observed in the real manufacturing system. These numbers are the input parameters for the model when the process planning is done for production. The maximum queue capacity for each workstation can depend on the other defined queues because during processing of a product to become complete, there has to be several cycles of production to be passed, in each of these cycles several processing stages need to be done in different workstations and depend on the processing time of each workstation, different number of queues will be created. These queue capacity levels can affect each other when there are consecutive stations that have the high processing time, so whenever the processing of each station is finished, it will add to the queue of the next processing station. This increase in the queue can lead to a workstation reach to its maximum level of queue capacity and request for adding a new machine. In the case study that is considered for this research, this dependency can be observed when the demand rate is high and queue of products will be added regularly. In the first cycle the robot has the highest processing time to assemble the cups and this will increase the number of queue that is increasing from the orders that are processing from AS/RS and vision quality control station. The maximum allocated queue capacity for the robot station can have impact on the quality control station when the processing is blocked and the quality control has to stop processing products because the flow is not available. In this way the maximum number of each can be related to each other.

The potential extension of the capacity planning simulation modelling approach can be using current discrete-event simulation model integrated with the robot agent that has several advantages in terms of using state charts behaviour model for constructing the possible agent rule and if-then-else conditions in order to balance the line and share its utilization rate possibly with the manual assembly station. The work in process products can receive the order of processing by the manual assembly station if they cannot be processed by the robotic assembly station, which also can provide the more smooth flow of production. Furthermore, in the case that robot station reaches to its maximum queue capacity level, it has the opportunity to request the route of the products, changes to

manual assembly station, where the utilization rate of the manufacturing system workstations can be balanced.

## **CHAPTER 5: CONCLUSIONS**

### **5.1. Conclusions**

Capacity planning and production control for different types of manufacturing systems created challenges for manufacturing companies regularly and they are trying to deal with customer order uncertainties in their production systems and how to decrease the impact of changes in product demands to the production processes through implementing applicable manufacturing control strategies. Simulation modelling techniques such as discrete-event, system dynamics and agent-based, would be a great benefit for them to build their desired functional requirements of all the production processes and conduct simulation experiments and relevant analysis. By taking advantage of simulation software, the risk of the failure for examining new planning and control methods for production line on physical level will be decreased efficiently.

Also in order to justify the use of simulation modelling, synthesis and analysis has to be differentiated in the context of simulation modelling. Synthesis is to design a new system considering the engineering design requirements of that system and technical aspects but analysis is to verify whether the design of the system is working properly or not. By using simulation modelling techniques, several analyses can be done for the designed system in order to illustrate different behaviours. With the analysis tools available in simulation software, the required performance of the constructed system can be analysed and verified by using different simulation scenarios. According to this process, the conceptual design of a new system can be verified by simulation analyses. Also, in order to improve the performance of the existing system, simulation tools should be used in the first stage in order to check the impact of assumed improvements on the existing system and producing an improved design of the system. In this research, the manufacturing system and the design are available and the simulation modelling is used in order to build a dynamic capacity plan for a scalability problem. The capacity planning for the reconfigurable manufacturing system and relevant analysis is demonstrated using simulation (i.e. AnyLogic).

Among the manufacturing systems that manufacturing industries are working on their development, the focus of this research is on reconfigurable manufacturing systems because it can cope with requirements of product variety easier and more effectively as well as finding a suitable and competitive solution for managing product variety. The problem that has been introduced in this research is to find a simulation modelling method to illustrate the scalability and change capability of a reconfigurable manufacturing system. The proposed discrete-event simulation modelling approach that is integrated with resources pool rules enabled analyses of changes in demand arrival rates and their impact on scalability and production flow. Moreover, introduction of resources pools and communication protocol into the discrete-event simulation model provides a solution for determining the required number of machines whenever the queue capacity level reaches its maximum defined level and preventing system blockage with added machines. Furthermore, the results of the simulation scenarios verified that the needed machines are added to the system when it is needed and are returned to the resources pool when they are idle. Also, the blockage problem that existed in the very first production scenario (i.e. DES only) is not happening any more.

There are several different factors that may affect the scalability of a manufacturing system. These factors can be, but not limited to, work in process (WIP) level during different shifts of production and the difference between desired and actual WIP level could be a good reason for increase or decrease the scale of the system. Moreover, by comparing the desired production rate (products/day) to the actual one and investigate closely into production lead time, there could be a good decision on changing the scale of the system for a reasonable time period. Also, capacity installation delay time, expected order rate and possible system breakdown are the other possible factors that can be considered at the same time of measuring other indicators. Furthermore, the seasonal cost of production compare to investment cost for changing the scale of the manufacturing system can be used for deciding on system rescaling purposes. In this research, queue capacity level for different workstations of a manufacturing system is considered as the main factor in order to find the required number of machines and make the production flow smoother which reduces the number of system blockage. This capacity planning

simulation modelling technique enables the manufacturers to know the maximum needed number of machines when order arrival rate changes.

The main contributions of this research can be summarized as following;

- Building a capacity planning simulation modelling framework for controlling the uncertain behaviour of the production flow
- Scalability planning of a reconfigurable manufacturing system to identify the number of needed machines during the production time
- Analyzing the trend of the re-scaling process in order to examine the chaotic behaviour according to the simulation results of dynamic capacity planning
- Analyzing the proposed scalable discrete-event simulation model by examining deterministic and probabilistic arrival rates
- Developing potential state charts for different modules of a reconfigurable manufacturing system to enable the behaviour modelling
- Developing possible agent rule functions for the robot module through state chart and if-then-else rules
- Constructing the simulation modelling framework based on a real reconfigurable manufacturing system case study (i.e. iFactory)

## **5.2. Engineering Thesis Questions**

After considering the development process of the proposed capacity planning simulation model and illustrating the results with their analysis and industrial significance, it can be claimed that the importance of having a smooth production flow and scalable capacity for reconfigurable manufacturing systems can be demonstrated by the proposed capacity planning simulation methodology. Furthermore, considering the following four typical engineering thesis questions are useful for the concluding remarks of this thesis.

### **1. The engineering problem**

Manufacturing industries are always faced with challenges of finding the optimal and cost-effective solution to adapt to the changes caused by fluctuations of customer

demands consist of changing in demand levels and order arrival rates. One of the main consequences of these changes is facing with large amount of work in process products, long queues and system blockage. The reconfigurable manufacturing system paradigm provides the benefits in terms of system modularity and changeable configuration but it is so costly and time consuming to change the system production plan manually in the physical system without knowing the output beforehand. Creating a simulation model of the system helps manufacturers and production engineers to examine different production scenarios with the simulation software. There are existing modelling techniques for the control of reconfigurable manufacturing systems but between these modelling approaches there is a lack in examining the scalability of reconfigurable manufacturing systems in terms of determining the number of needed machines during a single simulation run over different periods of production. This is the engineering problem that is considered and investigated throughout this research.

## **2. Limitations of previous solutions**

According to the literature survey that has been done in the second chapter, it is found that there are two main methods for the capacity planning of reconfigurable manufacturing systems, system dynamics simulation and mathematical programming. The proposed system dynamics simulation solutions are useful for finding near optimal investment policy during the long term and uncertain periods for changing the scale of the manufacturing system after a long time period. Moreover, the mathematical programming methods offered for the scalability planning of reconfigurable manufacturing systems used mixed integer programming and genetic algorithm principles to come up with a solution for the optimal capacity plan. These methods have the very complex structure and need a high computational time for finding the optimal solution which the results of these models might be very risky to be implemented for a physical system. Also, the proposed capacity planning models did not consider the requirements for the number of needed machines during the different production periods based on the maximum defined queue capacity level for different workstations.

### **3. Proposed solution**

A novel capacity planning simulation modelling methodology is proposed using discrete-event simulation integrated with resources pool functions in order to identify the recommended capacity (i.e. required number of machines) for a reconfigurable manufacturing system during a single simulation run. Also, examining the scalability of the manufacturing system as one of the important features of RMS is presented through investigating the simulation results and illustrating the changing behaviour of the re-scaling process. With this proposed solution the manufacturer can determine the needed number of machines for different workstations of a manufacturing system based on the maximum level of queue that can be defined for each workstation.

### **4. Proposed solution compared to previous solutions – benefits and drawbacks**

The key benefit of the proposed methodology is providing an easier and less complicated way to deal with the capacity and scalability planning of reconfigurable manufacturing systems through discrete-event simulation integrated with resources pools. The system dynamic and mathematical programming solutions for the capacity planning require special expertise and significant computational efforts to obtain the near optimal solutions not for the number of needed machines but for the investment policy selection of different configurations in comparison with the older manufacturing systems.

### **5.3. Future Works**

As the future works of this research using holonic control and multi agent-based modelling techniques can help in building an agent-based model of the system to investigate more on reconfiguration processes, change capability or even scalability of reconfigurable manufacturing systems. Moreover, the object-oriented design of the manufacturing system using UML state charts can give a clear possible idea for modelling of each agent in the system. Each agent behaves in collaboration with other agents in the system according to specified rules. These rules can be changeable, reusable and renewable when the manufacturing system is facing changes in production requirements such as introduction of new resources and processes to the system for

manufacturing a new product with reference to the availability and capability of the manufacturing system components to produce the new products.

Also, the introduction of agent-based logical modules such as reconfiguration agents can be a useful option to change the configurations of the iFactory layout model on a real-time basis. Also, the opportunity to introduce new system architectures using different production plans, material requirement plans, orders, resources and machines to illustrate possible new behaviours of different system modules can be considered. The examination of additional production scenarios can help to investigate the effectiveness of the simulation model.

In addition, based on the agent-based design framework of the reconfigurable manufacturing system, each logical and physical modules of the system have certain behaviours which are made using state charts behavioural modelling tool. When these modules contact to each other in different stages of production and because of the need to update the system to deal with production changes, different behaviours would emerge from this negotiation process. This emergent behaviour can be examined by analyzing the results of the agent-based simulation framework and the possible integrated model with discrete-event simulation as part of the future works. Some of these behaviours may not be easy to interpret because of the high complexity of the system which requires careful attention when building the simulation model.



## References:

- Allan, R. 2010. Survey of Agent Based Modelling and Simulation Tools. *Technical Report*, Computational Science and Engineering Department, STFC Daresbury Laboratory, Daresbury, Warrington.
- Alsafi, Y. & Vyatkin, V. 2010. Ontology-based reconfiguration agent for intelligent mechatronic systems in flexible manufacturing. *Robotics and Computer-Integrated Manufacturing*, 26, 381-91.
- Arai, T., Aiyama, Y., Sugi, M. & Ota, J. 2001. Holonic assembly system with Plug and Produce. *Computers in Industry*, 46, 289-299.
- Balasubramanian, S., Brennan, R. W. & Norrie, D. H. 2001. An architecture for metamorphic control of holonic manufacturing systems. *Computers in Industry*, 46, 13-31.
- Barata, J., Camarinha-Matos, L. & Cândido, G. 2008. A multiagent-based control system applied to an educational shop floor. *Robotics and Computer-Integrated Manufacturing*, 24, 597-605.
- Barbosa, J. & Leitao, P. Year. Simulation of multi-agent manufacturing systems using Agent-Based Modelling platforms. *In: Industrial Informatics (INDIN), 2011 9th IEEE International Conference on, 26-29 July 2011* 2011. 477-482.
- Barbosa, J., Leitão, P., Adam, E. & Trentesaux, D. 2015. Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution. *Computers in Industry*, 66, 99-111.
- Blanc, P., Demongodin, I. & Castagna, P. 2008a. A holonic approach for manufacturing execution system design: an industrial application. *Engineering Applications of Artificial Intelligence*, 21, 315-30.
- Blanc, P., Demongodin, I. & Castagna, P. 2008b. A holonic approach for manufacturing execution system design: An industrial application. *Engineering Applications of Artificial Intelligence*, 21, 315-330.
- Borshchev, A. 2013a. *The Big Book of Simulation Modelling: Multimethod Modelling with AnyLogic 6*, AnyLogic North America.
- Borshchev, A. 2013b. *The Big Book of Simulation Modeling: Multimethod Modeling with AnyLogic 6*, AnyLogic North America.
- Borshchev, A. & Filippov, A. Year. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. *In: The 22nd International Conference of the System Dynamics Society, 2004 Oxford, England*.
- Braatz, A., Höpf, M. & Ritter, A. 2003. AgenTec – Concepts for Agent Technology in Automation. *In: MAŘÍK, V., MCFARLANE, D. & VALCKENAERS, P. (eds.) Holonic and Multi-Agent Systems for Manufacturing*. Springer Berlin Heidelberg.
- Brito, T. B., Trevisan, E. F. C. & Botter, R. C. Year. A conceptual comparison between discrete and continuous simulation to motivate the hybrid simulation methodology. *In: Simulation Conference (WSC), Proceedings of the 2011 Winter, 11-14 Dec. 2011* 2011. 3910-3922.
- Bruckner, S., Wyns, J., Peeters, P. & Kollingbaum, M. 1998. Designing Agents for Manufacturing Control. *Proceedings of the Artificial Intelligence and Manufacturing Workshop*.

- Bussmann, S. & Sieverding, J. Year. Holonic control of an engine assembly plant: an industrial evaluation. *In: Systems, Man, and Cybernetics, 2001 IEEE International Conference on, 2001 2001. 3151-3156 vol.5.*
- Carpanzano, E. & Jovane, F. 2007. Advanced Automation Solutions for Future Adaptive Factories. *CIRP Annals - Manufacturing Technology, 56, 435-438.*
- Ceryan, O. & Koren, Y. 2009. Manufacturing capacity planning strategies. *CIRP Annals - Manufacturing Technology, 58, 403-406.*
- Colombo, A. W., Neubert, R. & Schoop, R. Year. A solution to holonic control systems. *In: Emerging Technologies and Factory Automation, 2001. Proceedings. 2001 8th IEEE International Conference on, 15-18 Oct. 2001 2001. 489-498 vol.2.*
- Deif, A. & ElMaraghy, H. 2007. Assessing capacity scalability policies in RMS using system dynamics. *International Journal of Flexible Manufacturing Systems, 19, 128-150.*
- Deif, A. M. & ElMaraghy, W. H. 2006. A control approach to explore the dynamics of capacity scalability in reconfigurable manufacturing systems. *Journal of Manufacturing Systems, 25, 12-24.*
- Dilip, K., Wu, S., Fleetwood, M. & Tamoto, H. 2003. Agent-based holonic design and operations environment for distributed manufacturing. *Computers in Industry, 52, 95-108.*
- ElMaraghy, H. 2005. Flexible and reconfigurable manufacturing systems paradigms. *International Journal of Flexible Manufacturing Systems, 17, 261-276.*
- ElMaraghy, H., Algeddawy, T., Azab, A. & ElMaraghy, W. 2012. Change in Manufacturing – Research and Industrial Challenges. *In: ElMaraghy, H. A. (ed.) Enabling Manufacturing Competitiveness and Economic Sustainability.* Springer Berlin Heidelberg.
- ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schonsleben, P., Tseng, M. & Bernard, A. 2013. Product variety management. *CIRP Annals - Manufacturing Technology, 62, 629-652.*
- Elmasry, S. S., Shalaby, M. A. & Saleh, M. M. 2012. A System Dynamics Simulation Model For Scalable-Capacity Manufacturing Systems. *The 30th International Conference of the System Dynamics Society.*
- Elmasry, S. S., Youssef, A. M. A. & Shalaby, M. A. 2014. Investigating Best Capacity Scaling Policies for Different Reconfigurable Manufacturing System Scenarios. *Procedia CIRP, 17, 410-415.*
- Fan, C. K. & Wong, T. N. 2003. Agent-based architecture for manufacturing system control. *Integrated Manufacturing Systems, 14, 599-609.*
- Fisher, K. 1999. Agent-based design of holonic manufacturing systems. *Robotics and Autonomous Systems, 27, 3-13.*
- Fletcher, M. 2002. Holonic Manufacturing System: Some Scenarios and issues. *In: Proceedings of the Workshop Intelligent Methods for Quality Improvement in Industrial Practice.*
- Giret, A. & Botti, V. 2009. Engineering Holonic Manufacturing Systems. *Computers in Industry, 60, 428-440.*
- Graefe, R. & Basson, A. 2014. Control of Reconfigurable Manufacturing Systems Using Object-Oriented Programming. *In: ZAEH, M. F. (ed.) Enabling Manufacturing Competitiveness and Economic Sustainability.* Springer International Publishing.

- Guță, S.-A., Dumitrache, I., Mcfarlane, D. & Masood, T. 2013. Rationales of Holonic Manufacturing Systems in Leather Industry. *In: MAŘÍK, V., LASTRA, J. M. & SKOBELEV, P. (eds.) Industrial Applications of Holonic and Multi-Agent Systems.* Springer Berlin Heidelberg.
- Gyulai, D., Kádár, B. & Monostori, L. 2014. Capacity Planning and Resource Allocation in Assembly Systems Consisting of Dedicated and Reconfigurable Lines. *Procedia CIRP*, 25, 185-191.
- Hasan, F., Jain, P. K. & Kumar, D. Year. Performance modeling of reconfigurable manufacturing system for different dispatching strategies under exception. *In: Industrial Engineering and Engineering Management (IEEM), 2012 IEEE International Conference on, 10-13 Dec. 2012* 2012. 593-596.
- Helal, M., Rabelo, L., Sepulveda, J. & Jones, A. 2007. A methodology for Integrating and Synchronizing the System Dynamics and Discrete Event Simulation Paradigms. Department of Industrial Engineering & Management Systems: University of Central Florida.
- John, K.-H. & Tiegelkamp, M. 2001. Building Blocks of IEC 61131-3. *IEC 61131-3: Programming Industrial Automation Systems.* Springer Berlin Heidelberg.
- Jovanović, M., Zupan, S., Starbek, M. & Prebil, I. 2014. Virtual approach to holonic control of the tyre-manufacturing system. *Journal of Manufacturing Systems*, 33, 116-128.
- Koren, Y. & Shpitalni, M. 2010. Design of reconfigurable manufacturing systems. *Journal of Manufacturing Systems*, 29, 130-141.
- Langer, G. & Alting, L. 2000. An architecture for agile shop floor control systems. *Journal of Manufacturing Engineering*, 19, 267-281.
- Leitao, P., Barbosa, J. & Trentesaux, D. Year. Bio-inspired multi-agent systems for reconfigurable manufacturing systems. *In, 2012 Langford Lane, Kidlington, Oxford, OX5 1GB, United Kingdom. Elsevier Ltd, 934-944.*
- Leitão, P., Colombo, A. & Restivo, F. 2003. An Approach to the Formal Specification of Holonic Control Systems. *In: MAŘÍK, V., MCFARLANE, D. & VALCKENAERS, P. (eds.) Holonic and Multi-Agent Systems for Manufacturing.* Springer Berlin Heidelberg.
- Leitao, P. & Restivo, F. Year. Agent-based holonic production control. *In: Database and Expert Systems Applications, 2002. Proceedings. 13th International Workshop on, 2-6 Sept. 2002* 2002. 589-593.
- Leitão, P. & Restivo, F. 2006. ADACOR: A holonic architecture for agile and adaptive manufacturing control. *Computers in Industry*, 57, 121-130.
- Leitão, P. & Rodrigues, N. 2011. Multi-Agent System for On-demand Production Integrating Production and Quality Control. *In: MAŘÍK, V., VRBA, P. & LEITÃO, P. (eds.) Holonic and Multi-Agent Systems for Manufacturing.* Springer Berlin Heidelberg.
- Lim, M. K. & Zhang, Z. Year. A multi-agent based manufacturing control strategy for responsive manufacturing. *In: 9th International Manufacturing Conference, 16-17 Aug. 2000, 2003 Switzerland. Elsevier, 379-84.*
- Lima, R. M., Sousa, R. M. & Martins, P. J. 2006. Distributed production planning and control agent-based system. *International Journal of Production Research*, 44, 3693-3709.

- Mařík, V., Vrba, P. & Fletcher, M. 2005. Agent-Based Simulation: Mast Case Study. In: CAMARINHA-MATOS, L. (ed.) *Emerging Solutions for Future Manufacturing Systems*. Springer US.
- Matsuda, M., Kashiwase, K. & Sudo, Y. 2012. Agent Oriented Construction of a Digital Factory for Validation of a Production Scenario. *Procedia CIRP*, 3, 115-120.
- Mehrabi, M. G., Ulsoy, A. G. & Koren, Y. 2000. Reconfigurable manufacturing systems: Key to future manufacturing. *Journal of Intelligent Manufacturing*, 11, 403-419.
- Meng, X. 2010. Modeling of reconfigurable manufacturing systems based on colored timed object-oriented Petri nets. *Journal of Manufacturing Systems*, 29, 81-90.
- Monostori, L., Váncza, J. & Kumara, S. R. T. 2006. Agent-Based Systems for Manufacturing. *CIRP Annals - Manufacturing Technology*, 55, 697-720.
- Negahban, A. & Smith, J. S. 2014. Simulation for manufacturing system design and operation: Literature review and analysis. *Journal of Manufacturing Systems*, 33, 241-261.
- Onori, M., Lohse, N., Barata, J. & Hanisch, C. 2012. The IDEAS project: plug & produce at shop-floor level. *Assembly Automation*, 32, 124-134.
- Ossama, M., Youssef, A. M. A. & Shalaby, M. A. 2014. A Multi-period Cell Formation Model for Reconfigurable Manufacturing Systems. *Procedia CIRP*, 17, 130-135.
- Paul, Van Brussel, H., Wyns, J., Bongaerts, L. & Peeters, P. 1998. Designing Holonic manufacturing systems. *Robotics and Computer-Integrated Manufacturing*, 14, 455-464.
- Putnik, G., Sluga, A., ElMaraghy, H., Teti, R., Koren, Y., Tolio, T. & Hon, B. 2013. Scalability in manufacturing systems design and operation: State-of-the-art and future developments roadmap. *CIRP Annals - Manufacturing Technology*, 62, 751-774.
- Roulet-Dubonnet, O. & Ystgaard, P. 2011. An Application of the Holonic Manufacturing System to a Flexible Assembly Cell. In: MAŘÍK, V., VRBA, P. & LEITÃO, P. (eds.) *Holonic and Multi-Agent Systems for Manufacturing*. Springer Berlin Heidelberg.
- Skobelev, P. 2011. Multi-Agent Systems for Real Time Resource Allocation, Scheduling, Optimization and Controlling: Industrial Applications. In: MAŘÍK, V., VRBA, P. & LEITÃO, P. (eds.) *Holonic and Multi-Agent Systems for Manufacturing*. Springer Berlin Heidelberg.
- Son, S. Y., Olsen, T. L. & Yip-Hoi, D. 2001. An approach to scalability and line balancing for reconfigurable manufacturing systems. *Integrated Manufacturing Systems*, 12, 500-511.
- Sugimura, N., Moriwaki, T. & Hozumi, K. 1998. A study on holonic manufacturing systems and its application to real time scheduling problems. In: OKINO, N., TAMURA, H. & FUJII, S. (eds.) *Advances in Production Management Systems*. Springer US.
- Van Brussel, H., Bongaerts, L., Wyns, J., Valckenaers, P. & Van Ginderachter, T. 1999. A conceptual framework for holonic manufacturing: Identification of manufacturing holons. *Journal of Manufacturing Systems*, 18, 35-52.
- Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L. & Peeters, P. 1998. Reference architecture for holonic manufacturing systems: PROSA. *Computers in Industry*, 37, 255-274.

- Venkateswaran, J. & Son, Y.-J. 2005. Distributed and Hybrid Simulations for Manufacturing Systems and Integrated Enterprise. Department of Systems and Industrial Engineering: University of Arizona.
- Vyatkin, V. 2011. IEC 61499 as Enabler of Distributed and Intelligent Automation: State-of-the-Art Review. *IEEE Trans. on Industrial Informatics*, 7, 768-781.
- Wang, F., Hou, Z.-G., Xu, D. & Tan, M. 2005. An Agent-Based Holonic Architecture for Reconfigurable Manufacturing Systems. In: WANG, L., CHEN, K. & ONG, Y. (eds.) *Advances in Natural Computation*. Springer Berlin Heidelberg.
- Wang, S. L., Xia, H., Liu, F., Tao, G. B. & Zhang, Z. 2002. Agent-based modeling and mapping of a manufacturing system. *Journal of Materials Processing Technology*, 129, 518-523.
- Wang, W. & Koren, Y. 2012. Scalability planning for reconfigurable manufacturing systems. *Journal of Manufacturing Systems*, 31, 83-91.
- Xiaobo, Z., Jiancai, W. & Zhenbi, L. 2000. A stochastic model of a reconfigurable manufacturing system Part 1: A framework. *International Journal of Production Research*, 38, 2273-2285.
- Zhengping, L., Cheng Hwee, S. & Low, M. Y. H. Year. A Survey of Emergent Behavior and Its Impacts in Agent-based Systems. In: *Industrial Informatics, 2006 IEEE International Conference on*, 16-18 Aug. 2006 2006. 1295-1300.

## VITA AUCTORIS

NAME: Kourosh Khedri Liraviasl

PLACE OF BIRTH: Tehran, Iran

YEAR OF BIRTH: 1991

EDUCATION: Azad University, Tehran, Iran, 2012  
University of Windsor, MEng., Windsor, ON, 2013  
University of Windsor, MAsc., Windsor, ON, 2015