

Schriftenreihe:
**Informationstechnische Systeme und
Organisation von Produktion und
Logistik**

Herausgeber:
Prof. Dr.-Ing. Bernd Scholz-Reiter

Band 18



**Feasibility of Autonomous Logistic
Processes Introduction of Learning
Pallets**

Afshin Mehrsai

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Tietjenstr. 60
28359 Bremen

ISBN 978-3-95545-056-4

Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliographie; detaillierte bibliografische Daten sind im Internet über <http://dnb.d-nb.de> abrufbar.

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Veröffentlicht im GITO Verlag 2013
Titelbild: © artstudio_pro - Fotolia.com
Gedruckt und gebunden in Berlin 2013

© GITO mbH Verlag Berlin 2013

GITO mbH Verlag
für Industrielle Informationstechnik und Organisation
Detmolder Straße 62
10715 Berlin
Tel.: +49.(0)30.41 93 83 64
Fax: +49.(0)30.41 93 83 67
E-Mail: service@gito.de
Internet: www.gito.de



Feasibility of Autonomous Logistic Processes Introduction of Learning Pallets

Vom Fachbereich Produktionstechnik
der
UNIVERSITÄT BREMEN

zur Erlangung des Grades
Doktor-Ingenieur
genehmigte

Dissertation

von

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Tag der mündlichen Prüfung: 09.10.2013

Acknowledgment

This work is dedicated to all those who have supported me throughout each level of my education. In particular, gratitude goes to my parents who always have supported and encouraged me throughout my life. I also acknowledge and appreciate the continuous support of my first supervisor from the University of Bremen: Prof. Dr. -Ing. Bernd Scholz-Reiter, Managing Director of the Bremer Institut für Produktion und Logistik (BIBA) GmbH and the new rector of the University of Bremen. I appreciate the kind encouragements from my second supervisor at the University of Agder: Prof. Dr. -Ing. Hamid-Reza Karimi, Professor of Control Systems.

Moreover, I would like to thank Dr. -Ing. Ingrid Rügge, the Manager of International Graduate School (IGS), for her kind supports. My colleagues at IGS have always been useful for referral and the exchange of new ideas. Furthermore, I wish to extend my appreciation to all colleagues at BIBA for their benevolence during the last three years.

Special thanks go to Kieserling Stiftung for financially supporting my work during three years.

September 2011

Abstrakt

Diese Dissertation adressiert die Dynamik der Distributionslogistik von Lieferketten und Produktionsnetzwerken sowie der Beschaffungslogistik von nach dem Werkstatt- und Fließprinzip organisierten Fertigungen. Diese Dynamik ist eine bedeutende Determinante logistischer Systeme, deren Beherrschung nicht trivial ist. Durch die Auswahl geeigneter logistischer Strategien, Systeme und Techniken kann den Herausforderungen dieses hoch dynamischen Umfelds begegnet werden. Die Entscheidung für bestimmte logistische Strategien, Systeme und Techniken hängt von der Beurteilung ihrer Machbarkeit und Akzeptanz in der Praxis ab. Unter diesem Gesichtspunkt entwickelt die vorliegende Arbeit einen Leitfaden für die effektive und effiziente Umsetzung selbstorganisierender logistischer Systeme am Beispiel des „Paradigma der Selbststeuerung in der Logistik“. Dieses Paradigma verspricht die Beherrschung der oben genannten Dynamik. Seine Anwendung ist jedoch bislang auf Labore und Technologiezentren begrenzt. Aus diesem Grund leistet die vorliegende Arbeit einen Beitrag zur Realisierung selbststeuernder logistischer Systeme.

Die Arbeit betrachtet Selbststeuerung in der Logistik aus der Perspektive selbststeuernder logistischer Prozesse und selbststeuernder logistischer Objekte. Erstere beschreiben logistische Planungs- und Steuerungsabläufe, während letztere ihre Operationen in Übereinstimmung mit den Prozessen ausführen. Hierfür gliedert sich die Untersuchung in einen konzeptionellen und einen empirischen Teil.

Im konzeptionellen Teil der Arbeit werden die Prinzipien konventioneller Planungs- und Steuerungssysteme in Produktion und Logistik aufgezeigt und ihr Leistungsvermögen beschrieben. Hiervon wird das Konzept selbststeuernder logistischer Prozesse abgegrenzt. Darauf aufbauend wird ein pragmatischer Leitfaden für die Implementierung selbststeuernder logistischer Objekte erarbeitet. Im empirischen Teil erfolgt eine Ausgestaltung dieses Leitfadens anhand eines konkreten selbststeuernden logistischen Objekts. Hierbei handelt es sich um sogenannte „learning pallets“ (Lpallets), die in Übereinstimmung mit den Anforderungen des logistischen Systems entwickelt werden.

Die Arbeit ist wie folgt aufgebaut. Zu Beginn werden „Advanced Planning Systeme“ vorgestellt, die Produktions- und Logistikabläufe in Wertschöpfungsketten organisieren. Im Anschluss daran werden typische Fertigungsformen in Wertschöpfungsketten näher betrachtet. Hier auftretende Planungsprobleme können mit der mathematischen Programmierung modelliert werden, deren Ergebnisse als Vergleichsmaßstab dienen können. Für die Umsetzung des Konzepts der Lpallets werden Methoden ermittelt, die den Anforderungen und Spezifikationen dieser selbststeuernden logistischen Objekte gerecht werden. Sensitivitätsanalysen im Rahmen von Warteschlangenmodellen erlauben es schließlich, das Verhalten von Lpaletten in der Werkstattfertigung und anderen Produktionsumgebungen zu untersuchen. Im Anschluss daran wird der Nutzen von Lpaletten mit experimentellen Untersuchungen verdeutlicht.

Abstract

This doctoral work complies with existing dynamics in outbound logistics, i.e., supply chains and production networks, as well as inbound logistics, i.e., shop-floors and production lines. This topic is recognized as a critical characteristic of the present and prospective business environment with outstanding exploration potentials. Nowadays, challenging with such a transient and dynamic environment depends on the selection of competent performing strategy, system, and techniques in logistics' operations. However, a decision for any new approaches is dependent on proper investigations in terms of feasibility and acceptability of the approach in practice. In this regard, in the current work a practical way is proposed for efficiently and effectively realizing the new approach to the self-organizing logistics system, called "*Autonomy paradigm in logistics*". This paradigm is basically initiated to handle new emerging features and conditions related to the subject of dynamics. Nevertheless, implementation of autonomy in practice is still limited to labs and technology parks. Thus, more research emphasis is required on this topic.

The current research essentially perceives the paradigm of autonomy in logistics by two aspects as: *autonomous logistic processes* and *autonomous logistic objects*. With this respect, the study is divided into conceptual and empirical parts with elaborations in both sections. In other words, the autonomous logistic processes typically deal with planning and scheduling processes. Then, under the autonomous processes the autonomous objects are supposed to control their operations autonomously, in accordance to the autonomous processes.

The early parts of this work are allocated to a deep investigation of conventional performances in logistics and production systems/networks. Here, the position of the autonomous logistic processes in the considered framework is delimited. Later, a pragmatic approach to the concept of autonomous logistic objects is elaborated. By sharpening and clarifying the target as well as the context of this research, the main attention is paid to the development of a feasible logistic object with the merit of autonomous control in shop-floor and production environments. This object, called *learning pallets* (Lpallets), is developed according to the conventional approaches in manufacturing systems.

In summary, the work is configured as follows. Initially, the advanced planning system (APS), for organizing production and logistics operations throughout supply chains (SC), is briefly explored. Afterwards, some prominent production systems, to be used by SC, are introduced. Next, mathematical programming is shortly explained for the performance of conventional planning and scheduling problems. For the idea of Lpallets, intelligent methods in compliance with the requirements and specifications of such autonomous objects are investigated. After that, a quick approach is assigned to queuing theory as a suitable methodology for sensitivity analysis of Lpallets within shop-floor and production environments. Subsequently, the main contributions of the Lpallets' concept are described and illustrated by several simulation experiments.

Table of Content

| | | |
|-------|---|-----|
| | Acknowledgment..... | i |
| | Abstrakt..... | ii |
| | Abstract..... | iii |
| | Table of Content..... | iv |
| | Abbreviations and Symbols..... | vii |
| | List of Figures..... | xi |
| | List of Tables..... | xv |
| 1 | Introduction..... | 1 |
| 1.1 | Overview..... | 2 |
| 1.2 | Motivation..... | 8 |
| 1.3 | Research Questions and Objectives..... | 11 |
| 1.4 | Dissertation Navigator..... | 13 |
| 2 | Fundaments in Logistics/Production System..... | 15 |
| 2.1 | Current Production Planning and Control..... | 16 |
| 2.2 | Logistics and Supply Chain Management..... | 27 |
| 2.3 | Dynamics and Autonomy in Logistics..... | 31 |
| 2.3.1 | Dynamics in Logistics..... | 31 |
| 2.3.2 | Centralized, Decentralized, and Autonomous Control Systems..... | 34 |
| 2.3.3 | Autonomous Logistic System..... | 38 |
| 2.3.4 | Autonomous Logistic Objects..... | 42 |
| 2.3.5 | Supply Chain and Production Structures..... | 44 |
| 2.3.6 | Shop-Floor Scheduling..... | 50 |
| 3 | Conventional Compatible Techniques (Research Approach)..... | 63 |
| 3.1 | Closed and Open System Review Towards Learning..... | 64 |
| 3.2 | Closed-Loop System vs. Complexity in SC Review..... | 67 |
| 3.3 | Material Flow Review..... | 72 |
| 3.3.1 | Material Push..... | 72 |
| 3.3.2 | Material Pull..... | 73 |
| 3.4 | Kanban..... | 74 |
| 3.5 | Conwip..... | 77 |
| 3.6 | Polca..... | 79 |
| 4 | Introduction of Learning Pallets and Applied Methods..... | 82 |
| 4.1 | Learning Pallets (Lpallets)..... | 83 |
| 4.2 | Artificial Intelligence..... | 91 |

| | | |
|-------|---|-----|
| 4.2.1 | Genetic Algorithm | 92 |
| 4.2.2 | Simulated Annealing | 99 |
| 4.2.3 | Tabu Search | 101 |
| 4.2.4 | Fuzzy System..... | 102 |
| 4.2.5 | Artificial Neural Networks..... | 113 |
| 4.2.6 | Multilayer Perceptron and Backpropagation Learning..... | 119 |
| 4.2.7 | Radial Basis Function Networks | 122 |
| 4.3 | Simulation..... | 128 |
| 4.4 | Mathematical Programming/Optimization | 130 |
| 4.5 | Queuing Theory | 137 |
| 4.5.1 | Arrival and Service Process..... | 139 |
| 4.5.2 | Open Queuing Network | 145 |
| 4.5.3 | Closed Queuing Network..... | 147 |
| 4.5.4 | Contribution of the queuing theory to Lpallets | 151 |
| 5 | Experiment Scenarios with Simulation | 153 |
| 5.1 | Integration of Lean-Agile Experiments with Autonomy in Supply Chains | 154 |
| 5.1.1 | Introduction of the Experiment..... | 154 |
| 5.1.2 | Agile Logistics | 155 |
| 5.1.3 | Autonomous Control System in Logistics..... | 156 |
| 5.1.4 | Logistics Performance Measures | 156 |
| 5.1.5 | Push vs. Pull System | 156 |
| 5.1.6 | Simulated Scenario | 158 |
| 5.1.7 | Simulation Run and Results | 159 |
| 5.1.8 | Conclusion of the Experiment..... | 162 |
| 5.2 | Optimization of Material-Pull in a Push-Pull Flow Logistic Network, using Meta-Heuristic and Fuzzy System | 163 |
| 5.2.1 | Hybrid Push-Pull Control | 164 |
| 5.2.2 | Problem Definition..... | 165 |
| 5.2.3 | Applied Genetic Algorithm | 166 |
| 5.2.4 | Simulated Annealing | 167 |
| 5.2.5 | Fuzzy Set | 168 |
| 5.2.6 | Experiment Results | 169 |
| 5.3 | Toward Learning Autonomous Pallets by Using Fuzzy Rules, Applied in a Conwip System | 172 |
| 5.3.1 | Mathematical Programming Representation | 173 |
| 5.3.2 | Lpallets in Pull System | 175 |

| | | |
|-------|---|-----|
| 5.3.3 | Simulation Results Analysis..... | 179 |
| 5.3.4 | Experiment Summary | 186 |
| 5.4 | Application of Learning Pallets in Hybrid Flow-Open Shop Scheduling, Using Artificial Intelligence..... | 187 |
| 5.4.1 | Hybrid Flow-Open Shop Problem | 188 |
| 5.4.2 | Assembly Scenario..... | 189 |
| 5.4.3 | Lpallets in the Scenario..... | 190 |
| 5.4.4 | Application of GA..... | 191 |
| 5.4.5 | Application of Fuzzy Inference System..... | 191 |
| 5.5 | Application of Radial Basis Function Network..... | 192 |
| 5.5.1 | Simulation Results | 193 |
| 5.5.2 | Analysis by Closed Queuing Network..... | 194 |
| 5.5.3 | Extended RBF Network | 197 |
| 5.5.4 | Extended Scenario and Results | 198 |
| 5.5.5 | Conclusion of the Experiment..... | 200 |
| 6 | Physical Implementation of Prototype..... | 202 |
| 7 | Conclusion and Outlook..... | 208 |
| 7.1 | Conclusion | 209 |
| 7.2 | Outlook..... | 211 |
| | References..... | 215 |
| | Appendix A..... | 236 |
| | Appendix B..... | 242 |

Abbreviations and Symbols

| | |
|-----------|--|
| AC | Autonomous Control |
| AgMS | Agile Manufacturing System |
| AGTPT | Average Global Throughput Time |
| AGV | Autonomous Guided Vehicle |
| AI | Artificial Intelligence |
| ALEM | Autonomous Logistics Engineering Methodology |
| ALTPT | Average Local Throughput Time |
| AMS | Autonomous Manufacturing System |
| ANN | Artificial Neural Networks |
| APS | Advance Planning System |
| ATP | Assemble to Order |
| ATP | Available to Promise |
| BCMP | Baskett, Chandy, Muntz, and Palacios |
| BD | Birth and Death |
| BOM | Bill of Material |
| BST | Best Selective Training |
| cdf | Cumulative Density Function |
| CIM | Computer Integrated Manufacturing |
| Cmax | Makespan |
| COG | Center of Gravity |
| Conv | Conventional |
| Conwip | Constant Work in Process |
| CP | Constraint Programming |
| CRC | Collaborative Research Cluster |
| CRM | Customer Relationship Management |
| CTP | Capacity to Promise |
| DBR | Drum-Buffer-Rope |
| DLRP | Distribution Logistics Routing Protocol |
| DP | Decoupling Point |
| DS | Detail Scheduling |
| DSS | Decision Support Systems |
| EDD | Early Due Date |
| EPF | Extended Product Form |
| ERP | Enterprise Resource Planning System |
| ETO | Engineer to Order |
| FAM | Fuzzy Associative Memory |
| FCFS/FCFO | First Come First Serve/First Come First Out |
| FMS | Flexible Manufacturing System |

| | |
|-----------|--|
| FSSP | Flow Shop Scheduling Problem |
| GA | Genetic Algorithm |
| GSBR | General Shifting Bottlenecks Routine |
| GTPT | Global Throughput Time |
| HMS | Holonic Manufacturing System |
| ICT | Information and Communication Technology |
| IMS | Intelligent Manufacturing System |
| IP | Integer Programming |
| JIS | Just In Sequence |
| JIT | Just In Time |
| JSSP | Job Shop Scheduling Problem |
| KPI | Key Performance Indicator |
| LCFS/LIFO | Last Come First Serve/ Last Come First Out |
| LeMS | Lean Manufacturing System |
| LMS | Least Mean Square |
| LN | Logistics Networks |
| LP | Linear Programming |
| Lpallets | Learning Pallets |
| LPT | Longest Processing Time |
| LTPT | Local Throughput Time |
| LVQ | Learning Vector Quantization |
| MA | Memetic Algorithm |
| MAS | Multi-Agent Systems |
| MILP | Mixed Integer Linear Programming |
| MINP | Mixed Integer Nonlinear Programming |
| MIP | Mixed Integer Programming |
| MLP | Multi layer Perceptron |
| MOM | Mean of Maxima |
| MOP | Multi Objective Programming |
| MPS | Master Production Schedule |
| MRPI | Material Resource Planning |
| MRPII | Manufacturing Resource Planning |
| MRT | Mean Repair Time |
| MS | Minimum Slack |
| MSE | Mean Square Error |
| MTF | Make to Forecast |
| MTO | Make to Order |
| MTS | Make to Stock |
| MVA | Mean Value Analysis |

| | |
|---------|--|
| neg-exp | Negative Exponential Distribution |
| NLP | Nonlinear Programming |
| NN | Neural Networks |
| NP | Nondeterministic Polynomial time |
| OEM | Original Equipment Manufacturer |
| OR | Operation Research |
| OSSP | Open Shop Scheduling Problem |
| PCA | Principal Component Analysis |
| pdf | Probability Density Function |
| pmf | Probability Mass Function |
| PN | Production Networks |
| Polca | Paired-Cell Overlapping Loops |
| pp | Page |
| PP | Production Planning |
| PPC | Production Planning and Control System |
| QLE | Queue Length Estimator |
| QRM | Quick Response Manufacturing |
| RBF | Radial Basis Function |
| RFID | Radio Frequency Identification |
| RMS | Reconfigurable Manufacturing System |
| RMSE | Root Mean Square Error |
| RO | Robust Optimization |
| RR | Round Robin |
| RTS | Real-Time Heuristic |
| SA | Simulated Annealing |
| SC | Supply Chains |
| SCM | Supply Chain Management |
| SCN | Supply Chain Networks |
| SCOR | Supply Chain Operations Reference |
| SD | Steepest Descent |
| SIRO | Service in Random Order |
| SN | Supply Networks |
| SND | Strategic Network Design |
| SNP | Supply Network Planning |
| SOMs | Self-Organizing Maps |
| SP | Stochastic Programming |
| SPT | Shortest Processing Time |
| SQ | Shortest Queue |
| STD | Standard Deviation |

| | |
|------|----------------------------------|
| TP | Throughput |
| TP | Transportation Planning |
| TPS | Toyota Production System |
| TPT | Throughput time |
| TSSE | Total Sum-Squared Error |
| VRP | Vehicle Routing Problems |
| VS | Vehicle Scheduling |
| WA | Weighted Average |
| WIP | Work in Process |
| WN | Wireless Network |
| WSN | Wireless Sensor Networks (Nodes) |

List of Figures

| | |
|--|----|
| Figure 1: Recommended constituent components of autonomous logistic processes..... | 13 |
| Figure 2: Dissertation navigator..... | 14 |
| Figure 3: Functional building blocks of production planning and control systems (PPC)..... | 17 |
| Figure 4: Market penetration of planning systems, inspired by [67]. | 17 |
| Figure 5: MRPI contribution to PPC..... | 18 |
| Figure 6: MRPII framework, adopted from [68] [69]. | 19 |
| Figure 7: Information flow in ERP System [74]. | 20 |
| Figure 8: Categorization of APS modules and planning structure, adapted from [75] [77] [78]. | 21 |
| Figure 9: An exemplary conventional supply network with each section's duty, adopted from [99]. | 30 |
| Figure 10: Classical APS with respect to implementing potential of autonomous control system, adopted from [75]. | 31 |
| Figure 11: Aspects of dynamics in logistics and manufacturing systems. | 33 |
| Figure 12: Control structures with autonomy domain interest, according to [114] [115]. | 35 |
| Figure 13: Exemplary central and distributed systems in technical systems with star connection.. | 36 |
| Figure 14: Effective elements in configuring autonomous control systems, according to [13]. | 38 |
| Figure 15: Cooperation of several research fields with the internet of things, see [132]. | 43 |
| Figure 16: Leagile supply chains by lean and agile strategies using push and pull control, adopted from [100] [157] [158] [159]. | 46 |
| Figure 17: The practical aspects contributing in the mass customization merit..... | 50 |
| Figure 18: Information flow diagram in a manufacturing system, adapted from [173] pp 10. | 52 |
| Figure 19: Exemplary flow-shop with 3 product types and 5 machines. | 57 |
| Figure 20: Exemplary shop-floor with 3 product variants and 5 working stations. | 58 |
| Figure 21: Exemplary open-shop problem with arbitrary selections for processing orders. | 59 |
| Figure 22: Information flow from master planning to shop-floor control with decentralized autonomous objects. | 62 |
| Figure 23: a) Open system with input from and output to environment, b) closed system. | 64 |
| Figure 24: Single-card Kanban. | 75 |
| Figure 25: Dual-signal Kanban using production and withdrawal (replenishment) cards. | 75 |
| Figure 26: Definition of takt time, cycle time, and lead time of leveled processes on six machines.. | 77 |
| Figure 27: Simple one-line Conwip system. | 78 |
| Figure 28: Polca control between production cells in an exemplary shop-floor, according to Suri [252]. | 80 |
| Figure 29: Features of realizing autonomous objects in logistics. | 84 |
| Figure 30: Exemplary outbound logistics with closed loop pallets circulation, authorized by third party logistics. | 85 |
| Figure 31: Exemplary a) Central control b) autonomous/learning pallets with intelligent controller, in shop-floor. | 86 |
| Figure 32: Conventional production planning, scheduling and execution process flows and its interaction in APS, adopted from [69]. | 88 |
| Figure 33: Performance of the assumed Lpallets in shop-floors and their interactions with other equipments and ERP system. | 89 |
| Figure 34: Symbolic input, controller, and output of Lpallets. | 90 |
| Figure 35: Encoding / decoding of a solution [282] pp 55. | 94 |
| Figure 36: Mutation by means of alternating alleles. | 94 |
| Figure 37: Permutation of two genes. | 95 |

| | |
|--|-----|
| Figure 38: Simple variants of crossover operation..... | 95 |
| Figure 39: PMX-crossover..... | 96 |
| Figure 40: OX-crossover..... | 96 |
| Figure 41: Cycle crossover (CX)..... | 96 |
| Figure 42: Simple flow chart of GA..... | 97 |
| Figure 43: Roulette-Wheel-Selection for individuals..... | 98 |
| Figure 44: General flow chart of simple simulated annealing algorithm..... | 100 |
| Figure 45: Simple flow chart of TS algorithm..... | 102 |
| Figure 46: Schematic mapping of member of fuzzy sets to membership degree with [0 1] certainty. | 103 |
| Figure 47: Triangular membership function..... | 105 |
| Figure 48: Trapezoidal membership function..... | 106 |
| Figure 49: Gaussian membership function..... | 106 |
| Figure 50: Intersection and Union of two triangular fuzzy sets..... | 107 |
| Figure 51: Minimum and maximum of two fuzzy numbers \tilde{A} and \tilde{U} | 108 |
| Figure 52: Mamdani fuzzy inference system (FAM) mechanism..... | 111 |
| Figure 53: Two neuron in communication via Synapse and Dendrite..... | 113 |
| Figure 54: A simple exemplary neuron with bias from a perceptron network..... | 114 |
| Figure 55: Some popular transfer functions..... | 114 |
| Figure 56: A simple multilayer perceptron network..... | 115 |
| Figure 57: An exemplary MLP with two layers..... | 120 |
| Figure 58: A simple RBF network with one-node output..... | 122 |
| Figure 59: An RBF network with multi-outputs..... | 125 |
| Figure 60: Exemplary simulation model of a car light assembly line located at BIBA institute, modeled by Plant-simulation..... | 129 |
| Figure 61: Linear membership function for i th fuzzy constraint..... | 134 |
| Figure 62: a) and c) the membership functions of minimization and b) the membership function of maximization objective..... | 136 |
| Figure 63: Details of processes in a queuing system in terms of waiting, processing, and departure times, adopted from [351]..... | 138 |
| Figure 64: The transition of $i \rightarrow j$ from t_1 to t_2 | 141 |
| Figure 65: Statistical equilibrium of state transition..... | 142 |
| Figure 66: State transition diagram of the BD process..... | 142 |
| Figure 67: Finite state process as special BD process..... | 143 |
| Figure 68: Exemplary of a general open queuing network..... | 145 |
| Figure 69: An exemplary closed queuing network..... | 148 |
| Figure 70: Production network scenario..... | 158 |
| Figure 71: Local TPT and global TPT in alternative scenarios..... | 160 |
| Figure 72: Global TPT, utilization and customer lead time under alternative scenarios..... | 161 |
| Figure 73: WIP, utilization, and local TPT under alternative scenarios..... | 162 |
| Figure 74: Exemplary push-pull network, with lasting each round trip 4 hours for transporters.. | 165 |
| Figure 75: Exemplary performance of the used GA crossover in breeding children for the next generation and encoding..... | 167 |
| Figure 76: The results for alternative scenarios in the presence of fuzzy sets and without..... | 171 |
| Figure 77: Applied fuzzy associative memory..... | 179 |
| Figure 78: Comparison of LTPT for LP, NoLP, and QLE in first pdf circumstance..... | 180 |

| | |
|---|-----|
| Figure 79: Probability density function of the average of all three types of products inflow in OEM. | 181 |
| Figure 80: Ratio of ALTPT to average of all alternatives with different lot sizes. | 182 |
| Figure 81: Ratio of ALTPT in pull to push for all alternatives with different lot sizes. | 182 |
| Figure 82: Comparison of LTPT for LP, NoLP, QLE.Fuzzy, and QLE in second pdf circumstance. | 184 |
| Figure 83: Comparison of alternatives with breakdowns in second pdf circumstance. | 184 |
| Figure 84: ALTPT in presence of different No. of Pallets, for all alternatives. | 185 |
| Figure 85: AGTPT in presence of different No. of Pallets, for all alternatives. | 185 |
| Figure 86: The prototype of assembly line located in the lab of BIBA Institute. | 188 |
| Figure 87: Possible permutations in operations order for the current experiment scenario and possible permutations in operations order (sequence). | 189 |
| Figure 88: Crossover in the used GA. | 191 |
| Figure 89: The applied FAM. | 192 |
| Figure 90: Topology of the applied RBF network for the experiment. | 193 |
| Figure 91: a) Makespan in every method, b) Stations working percentage in every method, c) Stations setup percentage in every method. | 194 |
| Figure 92: Closed loop assembly system (queuing network). | 196 |
| Figure 93: Waiting time and utilization with Plant simulation and WinPEPSY. | 196 |
| Figure 94: Sensitivity analysis for the number of jobs in queues, mean waiting time, and utilization with the use of closed queuing theory by WinPEPSY. | 197 |
| Figure 95: RBF network with unlimited RBFs in the hidden layer and three output functions to represent good, normal, and bad. | 198 |
| Figure 96: AFT with RBF vs. FIFO flow control in scenario 1 and 2. | 199 |
| Figure 97: Exemplary wireless sensor nodes. | 203 |
| Figure 98: Integration of WSN representing Lpallets in the rare light assembly scenario of CRC 637 by means of simulation and TCP/IP protocol. | 204 |
| Figure 99: A Java-based control system for monitoring the performance of connecting WSN by means of TCP/IP [394]. | 204 |
| Figure 100: Flow chart of processes of connecting WSN as Lpallets to assembly scenario. | 205 |
| Figure 101: Flow chart of Little's law controller inside WN for choosing next operation in real-time. | 206 |
| Figure 102: The general proposed framework in the study. | 211 |
| Figure 103: An exemplary cooperation between ANN, Fuzzy system, GA, and Gossiping (Epidemic) method for up-to-dating reactions to changes in an autonomous environment. | 214 |
| Figure 104: QLE without Fuzzy Supply Neg-Exp 55 min. | 236 |
| Figure 105: QLE with Fuzzy, Supply Neg-Exp 55 min. | 236 |
| Figure 106: QLE-Simple with flexible lot-size, Supply Neg-Exp 55 min. | 237 |
| Figure 107: QLE-Fuzzy with flexible lot-size, Supply Neg-Exp 55 min. | 237 |
| Figure 108: Conventional, Supply Neg-Exp 55 min. | 238 |
| Figure 109: Fuzzy Lpallet, Supply Neg-Exp 55 min. | 238 |
| Figure 110: The pdf of the entrance inter-arrival time for replenishment of semi-finished products to OEM that follows neg-exp distribution. | 239 |
| Figure 111: The pdf of the entrance inter-arrival time for replenishment of semi-finished products to OEM. | 240 |
| Figure 112: QLE, supply rate follow normal distribution with $\mu=55\text{min}$ and $\sigma=5$. | 240 |
| Figure 113: QLE with fuzzy, supply rate follow normal distribution with $\mu=55\text{min}$ and $\sigma=5$. | 241 |
| Figure 114: Fuzzy Lpallet, supply rate follow normal distribution with $\mu=55\text{min}$ and $\sigma=5$. | 241 |

Figure 115: The pdf of one type product at OEM that follows neg-exp distribution.242

List of Tables

| | |
|--|-----|
| Table 1: Evolution of ERP and APS [75] [76]. | 21 |
| Table 2: Demands of autonomous processes in different system levels, adopted from [110]. | 39 |
| Table 3: Levels of autonomy and their characteristics, done by [37]. | 41 |
| Table 4: Comparing lean and agility concepts by their attributes, adopted from [149] [156] [157] [158]. | 45 |
| Table 5: Contribution of autonomous control to environmental characteristics and enablers of mass customization. | 49 |
| Table 6: Used notations for open networks. | 145 |
| Table 7: Used notations in BCMP model for closed networks. | 148 |
| Table 8: Used notations in general form of MVA algorithm. | 150 |
| Table 9: Cycle times for each station for each product type in each plant. | 159 |
| Table 10: Applied notations in the problem. | 166 |
| Table 11: Processing times for each product on each line. | 169 |
| Table 12: Satisfaction degrees in SA for two alternatives with neg-exponential supply in Source plants. | 172 |
| Table 13: Performance of fuzzy rules with the presence of queue linguistic terms, using in extension. | 179 |
| Table 14: Representation of fuzzy rules without presence of queue linguistic terms. | 179 |
| Table 15: ALTPT in different alternatives for Conwip flow control. | 181 |
| Table 16: Ratio of ALTPT for each alternative to the average of all alternatives in same lot control system. | 183 |
| Table 17: Numerical experiments in alternative No. of Pallets and control method in Conwip with breakdowns. | 185 |
| Table 18: Comparison of simulation methods with classical scheduling algorithms. | 186 |
| Table 19: Processing times on each station. | 190 |
| Table 20: Numerical experiments for each method for all three products as flow times and makespan. | 193 |
| Table 21: Examined scenarios with three alternatives. | 199 |
| Table 22: Performance of RBF against flow-shop with FIFO (Permutation flow shop) in stations and flow times. | 199 |
| Table 23: Examined scenarios with the three alternatives. | 207 |
| Table 24: Performance of Lpallets with the use of Little's law. | 207 |

1 Introduction

1.1 Overview

Over the last three decades several changes have occurred in the business environment in terms of requirements and attributes. The markets are no longer stable regarding supply (offer) and demand [1] [2] [3] [4]. This phenomenon can be explained by several causes and effects on industries on the one side, and customers on the other side. In fact, the needs and desires of customers have been changing continuously, while they have been asking for announced and non-announced requirements. Moreover, close competitions in the markets, the globalization trend, and the scarcity of available resources, have triggered a bilateral provocation in supply, production, and delivery processes in general [5]. These all have led to various challenges, which have been propagated into every operation and activity of industries through various effects and appearances [6]. To compensate these downfalls in production and markets, industries are forced to organize cooperative procedures instead of isolated endeavors. Accordingly, these extensive consequences cause dynamic conditions in every aspect of industries. As a result, these dynamic situations are amplified by the current configuration of procurement, supply, production, and delivery activities in the form of supply networks (SN).

Today, it is obvious that isolated businesses are no longer able to sustain themselves in the modern market. It can be said that, gradually, the real competition over the market has been shifted from single units to supply chains (SC) [7]. To stay in this market, standalone companies were required to reconfigure their working procedures in a cooperative and collaborative manner. In other words, to deal with production and delivery difficulties, individual firms have joined together to construct stronger corporations in aligned structures of cooperative and collaborative industries. The firms with similar areas of work formed new organizations with connected members within SC and, similarly, SN [8]. In fact, the growing complexity of products in terms of shapes, characteristics, designs, and technologies, have brought about very complex structures in SC. Accordingly, the main roles of success have been given to SC with more sophisticated processes in their performances.

Generally, the extension in scale and scope of business units in the form of SC gives rise to complex operations all through the chains as uniform units. In this manner, disparate objectives, requirements, and performances of these units magnify any alternating and dynamic behaviors in material flow and information exchange between their members. In such an environment with dependent operations, any kind of changes to one side may have direct or indirect effects on the other side of SC. In case of SN, with more intensified correlations between the members, this situation is further exacerbated. Indeed, the members of SN are not simply connected in a linear structure, but in a network with additional affiliations. This combination violates the traditional direction of information and material flow within SC, i.e., from downstream to upstream and vice versa, respectively. Since interdependencies are intensified in SN, the lack of adequate coordination in performances or malfunctions in one unit can lead to chaotic networks over all [9] [10]. It is noticeable that in literature, several papers have different approaches

to the terms like SC, SN, supply chain networks (SCN), logistics networks (LN), and production networks (PN), and they are used alternatively in several cases [11]. Although some latest studies distinguish between these terms and consider some evolutionary specifications for each, others apply the general term of SC for all of them. In addition, sometimes logistics represents a common term for managing SC operations and processes. However, these terms are similarly treated in the current work. SC and logistics will be explained later in detail.

The causal effects in industries, which are evolved from the integration, span a wide range there, from restricted operations inside companies to interactions between members in SN. This broad range of possibilities and the causal effects make complex associations between them. Today, it is known from literature that complexity can be triggered by causal relationships and, at the same time, they have direct effects on emerging dynamic behaviors in industrial systems [12] [13]. However, the dynamics and complexities initiated by such interdependencies may occur in alternative locations (geographically distributed). In turn, this alternation amplifies the emerged complexities, following a positive loop. Basically, the existence of causal feedbacks in organizations causes multiple lags between the made decisions and their effects, which give rise to further complications. This holds specifically true for abundant operative systems like production and logistics networks. In this regard, recognition and control of such complexities with their causes and effects is quite essential. In other words, the causal effects— as the key initiator of complex behaviors [12]— must be recognized, controlled, and conducted in a proper way. Generally, this concept classifies the handling of such paradigms into two parts as: diagnosis and treatment. The feasibility study in this work complies with the diagnosis, and the suggested autonomous objects partially deal with treatment.

Nonetheless, recognition of the causalities is always a sophisticated and sometimes impossible task. Even in some cases recognition of the complex interactions does not assist the solutions to make things easier. This is because of the intricate nature of such holistic systems (e.g., SN) with full of interactions. That is why some research addresses the complex systems as bodies built of several entities and then directly deal with them, rather than considering the holistic systems, see [14] [15] [16] [17]. However, above the recognition, introduction of capable solutions to handle and reduce the complexities, dynamics, and causality phenomena, seems quite compulsory. In fact, those clever solutions must be able to handle such interdependent associations without being affected by the scale of the complexities. Concerning the difficulties of recognition, such solutions— by disregarding the detection of interactions— may just focus on the simplicity results. In doing so, the complex systems are considered as combinations of numerous elements that interact with and adapt to each other— as a characteristic of complex adaptive systems [17]—which get locally handled [16] [18] [19].

Since logistics and production systems are acknowledged as complex systems, managing their processes is a crucial and hard task. In this respect, the conventional techniques for planning and control have shown several limitations in managing the entire processes of

logistics and production networks on time and with proper outcomes. Whereas industrial operations are taking place in different topologies, the respective planning and control activities need to cover every process in order to effectively manage the entire system. Nevertheless, the conventional techniques with centralized attitude are not competent enough to comply with these requirements, and they show some drawbacks [20]. Although, the state of the art in communication and computations supports, to some extent, the conventional methods to meet a greater range of operations, still the accompanied complexities restrict their handling capabilities. These shortcomings with traditional systems in organizing all operations and processes by an integrated approach have stimulated the inquiry for new methods and techniques.

Recently, research on the issue of complexity and dynamics in SN [21] [22] has surged. Indeed, this rise in interest reflects the growth in networks' intricacies regarding their dynamic constraints and objectives. Today, it is clear that complexity and dynamics are mutually dependent phenomena in networks and are mostly used together in literature, see [23] [24] [25]. Generally, dynamics in SN can be classified into internal and external ones. Those challenges, including any changes or interruptions inside the networks, are clustered in internal dynamics and those causes happening to the business environment are considered as external dynamics. For instance: fluctuating and turbulent demand, rigid requirements concerning right products at the right time, place, and quality, competitors pressure, and scarce resources, are just some external dynamics happening to SN. On the contrary, supply uncertainty, Bullwhip effect, urgent internal orders, machines' breakdowns, and evolved bottlenecks, can be seen as internal causes and effects in SN. It is noticeable that existing dynamic behaviors (dynamics) in a system, from system dynamics methodology point of view, are classified into causes and effects with feedbacks [26] [27]. The causes are those stimulants that trigger some impacts (effects) maybe in the same place and time or with delay and shift.

However, by increasing the correlations (interrelations) between the members of SN a synergy happens to proliferation of dynamic challenges throughout the members. This holds specifically true when an integrated approach for coordinating all operations and processes within a supply network is centrally accomplished. To clarify it, SN in their new perspectives— as complex interactive networks— are configured out of several agents (firms) which transact with each other for a common target (in short or long term). Indeed, production and logistic systems are treated as compositions of several entities, e.g., logistic processes and objects, members in SN, and similar resources, although with different performance techniques. As shortly mentioned, every agent in this system has its own local constraints and goals that may be heterogeneous to the others (called conflicting objectives) [28] [29]. This situation burdens excessive efforts on the coordination task of SN, which after a certain threshold; improper performances are expected in SN (inspired by the fact of bounded rationality in any complex system). However, coordination of SN is a complicated mission for managers, which has a plenty of room to be investigated [30]. Researchers have shown that this is not a trivial task, so that several tactics have been introduced to challenge with the difficulties of coordinating complex processes in SN.

Furthermore, the notion of coordination for complex interactive networks seems quite relevant for delivering desirable results. In spite of several coordination policies, it is impossible to expect required outcomes, while the system heads to chaotic features. In this manner, regarding the complexity of the system (network) a suitable coordination policy must be undertaken [31].

Generally, two main approaches exist to the coordination of SN operations (in macro and micro perspective) by centralized and decentralized control. Conventionally, it is assumed that the control and the coordination of a system with abundant units are inclined to be centrally accomplished through integration [32]. In this manner, it is believed this holistic approach to the coordination task supports synchronization of every decision in accordance to the entire information (constraints) available about the system. Nevertheless, this concept faces some impediments when confronted with uncertainty, the lack of proper information, and a plenty of sophisticated (nonlinear) interdependencies between the collected data for the central coordinator [33]. This bulk of dynamic variables, constraints, and objectives, to be coordinated and optimized in a contradictory environment, results in hard problems either with non deterministic polynomial time (NP) algorithms or infeasible solutions. Besides, time lags in decision makings can easily damage appropriate as well as on-time reactions (or corrective actions) in such environments. Thus, it can be generally concluded that this kind of conventional policy with a central coordinator can be used for strategic and long term plans in SN. Because in strategic and, to some extent, tactical decisions, a general perspective to the assumed network is required with an aggregated data collection.

On the contrary, some other policies are required to tackle the shortcomings of the conventional coordination in the current dynamic and distributed SN, e.g., see [34]. Recently, a new approach has been presented, which retains the autonomous nature of agents (members/units) in complex networks. This new approach is called autonomy in logistics, see CRC 637 research cluster at <http://www.sfb637.uni-bremen.de>. In this case, whereas the notion of coordination's necessity is kept, a general problem is spread into distributed sub-problems. Therefore, the mission of solving these distributed (sometimes disparate) problems is carried out in a decentralized performance. In other words, a global problem is fragmented into several sub-problems corresponding to each unit of the network to get solved separately, still with awareness of the entire system. Moreover, instead of making a global decision for coordinating all the operations, based on aggregated collection of every constraint and available information, here, each autonomous unit makes its own decision for its own local (domestic) problem, constraint, and goal [31]. This approach refers to the nature of SN as holistic systems (bodies) configured out of several entities with autonomous inheritances. However, before the new achievements in the state of the art in information and communication technology (ICT), it has been hardly imagined about coordination of a dispersed system in a decentralized manner.

Accordingly, the pragmatic framework of this type of coordination is still an interesting subject for researchers. Whereas it is believed without coordinating features in such systems no appropriate result can be attained, there are several developing studies regarding the level of centralized and decentralized performances [35]. Currently, various explorations are being conducted to define a suitable tradeoff between local decisions in a network and global negotiations over a consensus, regarding the overall objectives. Not only the issue about (de)centralization plays a crucial role in this approach, but also the control and authority structures in terms of being hierarchical in contrast to heterarchical features are important as well [36] [37] [38]. In this regard, yet the question is how to combine the diverse aspects of distinct entities in a network with respect to the integration of effectively coordinating the entities.

For this purpose, a spectrum of authority structures can be assumed. On one extreme side of that spectrum, a fully hierarchical system with master-slave architecture is placed and on the opposite side, there is a fully heterarchical system based on equality for all entities, e.g., see [39]. Correspondingly, to some extent, the general authority in sub-systems of a network organization may span from passive to active, and even to proactive, performances. Indeed, this specific range is the subject of studies in the field of networks' coordination and control by means of self-organizing entities [40]. Idealistically, this range of research tends to achieve fully heterarchical systems, without being organized by any seniors or coordinators. However, it can be seen that the coordination and the control are the protecting factors against leading into complex chaotic systems in such environments [37] [41].

Similarly, several decentralized tactics have been newly applied to coordinate operations over SN and inside the member companies. For instance, adaptive systems by assistance of control theory as well as multi agent systems (MAS) are two methods based on adaptive intelligence and negotiation (tradeoff), which are abundantly referred in the literature, e.g., see [42] [43] [44] [45] [46]. With regard to the results of the current study and other scientific papers, it seems without having any interdisciplinary approach— for properly conducting decentralized systems— the decentralized coordination task leads to abortion. In this respect, various features of decentralized controlled and coordinated networks have been deeply explored by experts. To some extent, decentralized networks are configured out of autonomous entities with the competency of making decisions in different authority levels. Autonomous units employ the merit of autonomous control to manage and modify own performances in achieving their own objectives. Nonetheless, the objectives can be individual (local), clustered (comparable), or general (global) in networks.

Basically, by drilling down through the autonomy levels in SN and production organizations, a broad scope of units can be found to become autonomous candidates. It is believed from member companies in SN— in macro scale— to production and logistic objects like machines and pallets— in micro scale— altogether can be covered by the competency of self-organization and autonomous control paradigm, see relevant literature [34] [47] [48] [49]. In fact, this activity induces a transition of a competency from a system

to its sub-systems and entities [50]. So, the specific purpose of this type of performance is to redesign complex systems with far-simplified processes and functionalities to tackle intricate dynamics, since they cause complexities.

Conventionally, in order to cope with the emerged dynamics in manufacturing and SC environments several strategies have been developed during the recent decades. For instance, the most popular and reliable paradigms between production and organizational strategies are: the lean manufacturing system (LeMS), the computer integrated manufacturing (CIM), the flexible manufacturing system (FMS), the agile manufacturing system (AgMS), the reconfigurable manufacturing system (RMS), the intelligent manufacturing system (IMS), the holonic manufacturing system (HMS), and the autonomous manufacturing system (AMS) [51] [52] [53] [54]. These strategies have been presented in compliance with the continuously changing requirements in industrial environments. Additionally, several techniques have been examined to bring the aforementioned strategies into reality, e.g., MAS has shown promising performances in contributing to some of the strategies like HMS and AMS.

In that order, it can be argued that the strategies in manufacturing environment have had an evolutionary development concerning current abilities (the state of the art) and requirements. Generally, it is assumed that the successor strategies have included the prominent specifications of their predecessors into their own targets. This trace appears quite relevant in every extension or evolution of execution systems in industries. Therefore, in the current study, this outstanding characteristic is top concerned to be followed as well. Here, the contribution of the autonomy paradigm to the above strategies is tried to be elaborated throughout the research. Moreover, to define the position of AMS, as the latest strategy for logistics and manufacturing systems, the previous systems should be explored and traced.

By reviewing the major characteristics of each mentioned manufacturing system some coherent chains can be distinguished between them. For example, as Sarkis [55] describes FMS is a tool to move manufacturing capabilities from the mass production environment towards production of alternative types, volume and processes of products, as mixed mode production setup environment. Then, after the introduction of HMS, the notion of cooperating units (holons) in a holistic system came into practice. The units here, to some extent, reflect the independencies and contributions in decision makings. However, initially, in HMS the holons were rather considered as semi-autonomous objects than having complete autonomy in their decisions and performances. By reviewing some literature, it was found out that holons in a system have some limited awareness of the global objectives and cooperate with each other to achieve them. That is why some earlier literature noticed the fact that the holons are not given a fully independent authority in their decisions and operations, while they may be a part of another holon (i.e., moderated autonomy), e.g., [52] [53]. In fact, it can be said that holons are the units with moderated autonomy.

Accordingly, it is sometimes difficult to distinguish between the context of HMS and AMS [56] [57]. Modern strategies in organizing and control of manufacturing as well as logistics activities have a similar basis in such a way that they mostly exploit common theories and technologies to adhere to their targets. Practically, they may have lots of contributions, so that it is difficult to say they are basically different strategies. It is experienced that HMS rather deals with production environments. For example, when the drilling down through the autonomy scale reaches the level of shop-floors and manufacturing environments, it resembles HMS with bottom-up architecture design [53]. On the contrary, autonomy in macro-scale, e.g., for SN, should be explained by other generic concepts like autonomy paradigm in general or by collaborative agent systems [58] [59] [60]. At the same time, it can be seen that the later strategies, e.g., HMS, AMS, based on modern technologies, follow the targets of agile systems in a generic sense. Hence, it is fair to say the practical aspects of HMS and AMS are located in the functional targets of LeMS, FMS, and AgMS. To this effect, throughout the development of the current study the existing contributions between the pioneer AMS and its predecessor strategies is highlighted.

Now, after becoming familiar with the core area of the current study, briefly describing the general motivation of similar researches in this field is favorable. In fact, it justifies the following introductions and definitions used in the work.

1.2 Motivation

Generally, the main concern of this study and other similar research clusters, which work on the topic of autonomy in logistics, is to deal with existing complexities and dynamics embedded in the current and prospective logistic processes. Particularly, this issue is called “*Dynamics in Logistics*” as the comprehensive topic to be investigated. This has been stimulating several explorations over diverse topics in industries; among them, the concepts of autonomy and autonomous control are the prominent ones. Therefore, managing dynamics in logistics may involve different tactics and contributions of science with an interdisciplinary approach to all of them. However, the contribution of autonomy in logistics is underscored by the current study. Generally, a shortcoming has been seen in most studies on autonomy in logistics. In fact, no rich justification exists to directly reflect the contingency of employing autonomy paradigm with already developed strategies and practices in manufacturing industries. Initially, it was tried to focus on this issue, which approximates the concept of autonomy in logistics with the current requisites in production strategies. This study aims to justify the advent of autonomy in logistic processes with contributions to state-of-the-art strategy. In other words, the eagerness in the research for making self-organizing units has to be compatible with the relevant requirements in practice.

Accordingly, since the beginning of the current research, a bilateral approach has been introduced to face dynamics in logistics. The first approach tries to overwhelm the effects of dynamics, caused by internal or external stimulators. In fact, the causal (cause and effect) relationships—introduced by system dynamics— have inspired the first perspective on dynamics, i.e., system dynamics is a leading-edge academic method to

systematically study and deal with dynamic behaviors in systems [61]. In this manner, the dynamics are considered as undesirable effects in the steady states of any system. On the other hand, the second approach attempts to undertake dynamics as competitive advantages and to adopt them into own processes, for becoming more flexible. For example, autonomous objects in manufacturing environments, with quite flexible decision making capability, or autonomous members in SN are some aspects of this second approach to the dynamics. Correspondingly, the study over dynamics in logistics has been handled based on the two aforementioned approaches.

Initially, it is perceived that the first approach has been a traditional reaction to any changes and unforeseen events happening to industrial operations. Thus, several earlier strategies given to industries defined their main efforts in accordance with moderating and eliminating the dynamics in processes. For instance, LeMS follows a philosophy which, tries to reduce any kind of wastes (material or activity). On the other side, it aims at aligning all processes, in order to cut the unforeseen changes or fluctuation. This holds true, while the dynamics are avoided as much as possible. However, some incentives are considered there for making operations easier, which leads to flexibility in operations. Another example to be mentioned is AgMS that highlights responsiveness to customers' demands as a target and encourages employment of any techniques, like flexibility in processes, to achieve the goal [54]. As it has been seen, the role of flexibility is emphasized by AgMS, which is often considered as the successor of LeMS. However, these two strategies are some practical examples for the two aforesaid approaches looking at dynamics in industrial processes. Both strategies consider the essence of changes in business and operational environments, but they use different tactics. Nonetheless, LeMS indirectly tackles the dynamics (as non-desirable changes) by focusing on increasing the operational effectiveness, efficiency, and productivity. In fact, the strategy deploys its functionality in preferably stable business circumstances and may get into troubles when facing highly dynamic states. On the contrary, AgMS explicitly reflects the issue of continuous changes and dynamics in business environments and defines some strategic ways to handle them [62].

However, the important factor in all the mentioned strategies is that they mainly define some strategic philosophy or goals, often without any specific tools or techniques to realize them in practice. It means the relevant techniques and methods have been continuously developed, regarding the appealed goals, by academia and practitioners, and then have been dedicated to the corresponding systems. For instance, the concept of virtual enterprises is considered as a technique in compliance with the goals in AgMS, or agile design of products based on intelligent methods and ICT. The techniques are required to face dynamics and continuous changes with a reactive and even proactive manner to avoid undesirable events. The reactive categories may be placed in the vicinity of the first approach, aiming at limiting dynamic effects, while the proactive ones preferably can stick to the second approach with adoption of flexible and dynamic processes. However, such techniques to deal with dynamics in processes, reactively or proactively, are not broadly addressed in literature. Meanwhile, some other systems, like FMS, are placed between the

two approaches. FMS can reflect the essence of dynamics, but only reactively adapts itself to the changes, in contrast to the AgMS [62].

Basically, AgMS can be understood as a strategy rather than a simple technique that requires pragmatic methods and tools to be implemented on reality. A promising technique to realize some aspects of AgMS—by employing the competency of state-of-the-art—is the autonomous control, applied in manufacturing and logistics environments. In fact, this new approach to controlling processes in such environments gives rise to the required flexibility, simplicity, pro-activeness, and responsiveness as the attributes of AgMS or other strategies with similar properties. Nevertheless, accomplishment of such technique necessitates reconfiguration of infrastructures, changes in the current style of executions, and redesigns of authority's structures as the utmost importance.

After recognizing some existing strategies, pertinent to the two approaches in dynamics, the relations between the current study—by focusing on the feasibility of the autonomy in logistics—and the practiced systems in industries need to be defined. The author believes that this fact can be achieved through several investigations. These explorations have to delimit and amplify the common characteristics of the autonomy paradigm as well as the already practiced strategies. Similarly, they need to design new methodologies to configure both parties simultaneously. In order to bring the concept of autonomy and self-organizing objects closer to the appeals of industries, the autonomy is required, for instance, to be located in compliance with AgMS. Therefore, the contributions of AgMS to dynamic challenges in SN and production systems should be revealed. Following that, the contributions of AMS to AgMS as well as to the dynamics is needed to be studied. In particular, the idea of autonomous objects in logistics, as a target of AMS, is underlined in structuring the output of the current work.

As briefly mentioned, in the autonomy approach the aim is to assign local problems to local responsible units without propagating them to other centers or following others' commands. The units are autonomous or self-organized modules with the ability of making decisions. The decisions of the units are made based on the local constraints, local decision rules, local objectives, and information exchange between the units. Generally, it is believed and, to some extent, justified that distribution of tasks between decentralized decision making units largely contributes to the purpose of simplification of complex systems. Over the last two decades, this new approach has spanned several comparable terms in industrial researches. For example, as Windt *et al.* in [13], Scholz-Reiter *et al.* in [52], and Wiendahl *et al.* in [63] argue, the terms include: plug and produce (play) system, modular system, agent system, holonic system, intelligent system, self-organizing system, self-managing system, autopoiesis, as well as autonomous cooperation and control. However, among them, the recent term as autonomous control is progressively deploying itself over several applications in industries.

Accordingly, after some investigation for logistic objects with the competency of becoming autonomous, pallets in material pull control systems have shown the biggest motivation.

Indeed, few conventional material flow systems exist that reflect some specifications of autonomous control in their own performances. A great characteristic of pull control systems is their decentralized control aspect, which is mostly used in complex controlled environments. Indeed, this specification— originally offered by the material pull mechanism— is one of the most underlined attributes of autonomous control in manufacturing and logistics. Pull control regarding its approach to individual orders seems the most consistent mechanism to develop autonomous logistic objects with individuality. These consistencies between the paradigms became a strong incentive for initiating the learning pallets' (Lpallets) idea and employing them in pull-controlled environments.

Furthermore, the autonomous control has several specifications that must realize them to represent its functionality in practice. The prominent characteristics of this paradigm are distribution, decentralization, interaction, modularization, self-adaption, self-decision making, heterarchical structure, non-deterministic and uncertainty, as well as intelligence. Some of these characteristics are proportional and may get several trade-offs or delimitations in different applications. Despite the fact that autonomy has an absolute context, but in logistics and production systems it may not be seen as an absolute characteristic. These are some features with the requirement to be more investigated. Therefore, a feasibility study for defining the right contribution of autonomy to the conventional practicing logistics and production systems is favorable. Conclusively, achieving a feasible approach in the concept of autonomy, which can be directly applied by current industries, has motivated the present work.

1.3 Research Questions and Objectives

However, still a huge gap exists in the reconfiguration of logistic processes in SN (as complex systems), so that they can adopt autonomy and adjust it with current requirements in complex performing systems. Since this new approach is under investigation and is developing continuously, it has several potentials to be improved.

Here, it is tried to answer the questions around feasibility and compatibility of the autonomous control in logistics, with the purpose of being directly employed by industries in practice. For this purpose, after selecting the type of industries for exploiting the autonomy paradigm, some congruent production and logistic strategies with the notion of autonomy are required. Those strategies that convey the competencies of the autonomy paradigm in their respective characteristics or targets are the core incentive of this ideology. Investigation of these systems reflects the requisites of several methodologies with the functionality under uncertainty. After answering the question about which compatible logistic system can comply with the merit of autonomy, it is necessary to find a practical way for implementing the new paradigm on them. For this purpose, practical logistic objects have to be characterized with the aptitude of autonomous control, which connect the chains between autonomous logistic processes and the current practiced strategies. This has to be done with the aim of approximating autonomy to the state-of-the-art in logistics.

The ontology, the structure, and the techniques to be employed by autonomous processes and objects, are the fundamental issues to be investigated. Additionally, the level of autonomy, compatible methods, and suitable objects to be exploited, are some research questions about the concept of autonomy in logistics. In general, the arisen research questions as well as research objectives include:

- The degree of autonomy in terms of decentralization and heterarchical control in strategic, tactical, and operational levels → autonomy for operational level.
- Definition of autonomous control system for the respective logistics and production systems → autonomous processes beside autonomous objects, see Figure 1.
- Compatibility and contribution of the autonomy concept to the current practiced strategies in industries → LMS, AgMS, Leagility, mass customization.
- Contribution of autonomous control system to the well-known industrial problems like: scheduling, inventory control, and material flow control → by the use of pull control systems.
- Finding compatible logistic objects to be capable of autonomous control as well as applicable to current production systems → Lapllets in pull control systems.
- Capable methodologies and techniques for the autonomous units (Lpallets), i.e., configuration of autonomous control methodologies → intelligent techniques like ANN, GA, and fuzzy system.
- Analysis methods for evaluating the performance of autonomous control in the form of autonomous logistic objects → queuing theory.

All in all, the current study looks for a suitable framework, which can approximate the concept of autonomy to the state-of-the-art in practices of manufacturing industries. Within this framework, a feasible logistic object is to be introduced that reflects the notion of autonomous control in logistics. The specific developed object needs to be in compliance with the targets of LeMS, AgMS, and AMS. These objects (Lpallets), in this study, have to transfer the autonomous control idea into direct applications of shop-floors as well as outbound logistics. However, in order to develop Lpallets some intelligent techniques have to be employed, so that they inspire the merit of autonomy. These techniques encompass general methods in artificial intelligence (AI), particularly those methods with decision making and learning ability in complex environments, e.g., artificial neural networks (ANN), fuzzy inference system, and genetic algorithm (GA).

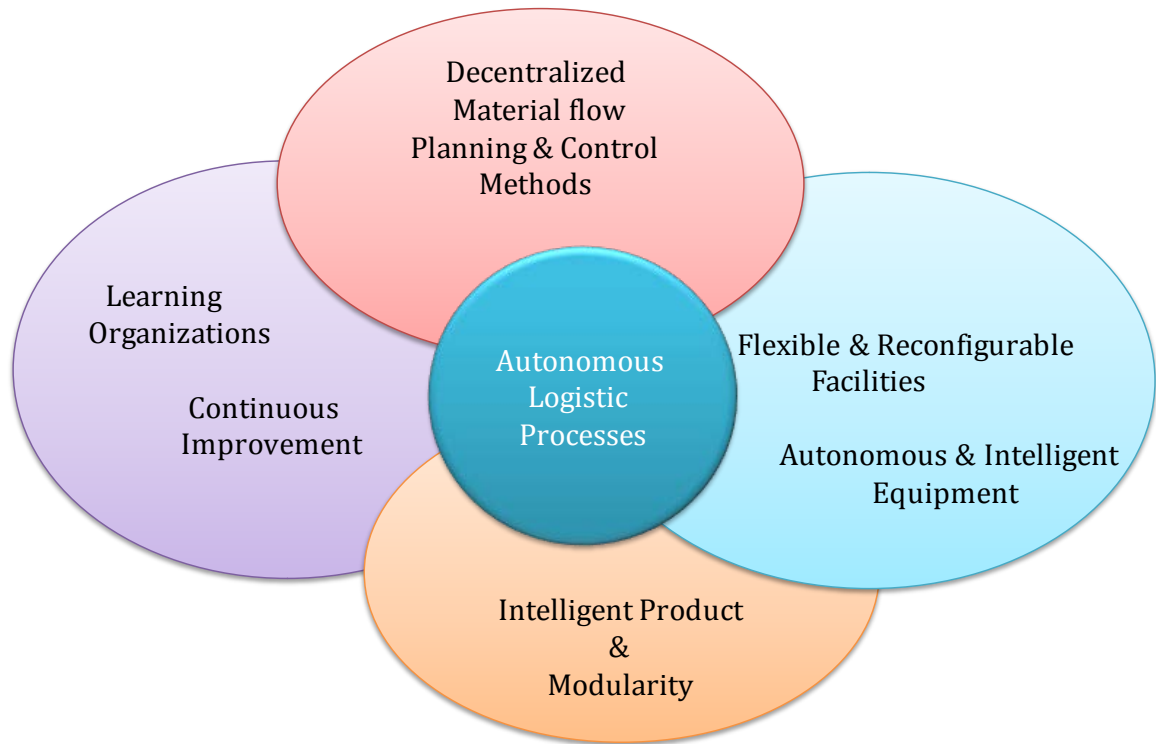


Figure 1: Recommended constituent components of autonomous logistic processes.

Moreover, some hypotheses that have been motivated the current study and have to be kept throughout the work are following:

- New introduced strategies for manufacturing industries are in compliance with their predecessors, but capable of solving the current problems.
- AgMS holds the targets of LeMS with some coherent aspects.
- AMS is a strategic system successive to FMS, AgMS, RMS, HMS, and IMS, that can simplify complex operations and improve flexibility of systems under dynamic situations.
- Implementation of AMS in industries requires illustrating its boundaries, respectively, limitations, potentials, and contributions.
- Logistics addresses operations and business processes in manufacturing and production industries.
- Autonomous control system context is reflected into relevant business processes as well as potential physical objects in logistics.
- Autonomous units are those components with intelligence capability to make decisions by their own, according to their local circumstance and available data.
- Learning is the main attribute of intelligent systems (objects), which can be realized by means of intelligent methods and computational intelligence.

1.4 Dissertation Navigator

For the sake of simplicity, the general format of the current dissertation is structured as follows, see Figure 2. The next chapter introduces several fundamentals relevant to the

current work, explaining about logistics and autonomy in general. Chapter 3 addresses the conventional systems practiced by current industries, which have the capability to reflect autonomy in their own processes. Generally, in chapter 2 and 3 the major part of the feasibility study is accomplished. Chapter 4 poses the main contribution of the current work as the concept of Lpallets to be employed by material pull industries. In this chapter, the applied and some potential methodologies to be used by Lpallets in practice are introduced. Afterwards, some experiments for the recommended thesis of the study are elaborated in chapter 5. Concisely in chapter 6 a physical implementation scenario is discussed with the approach towards developing a prototype. Conclusion and further works of the current study are given in chapter 7.

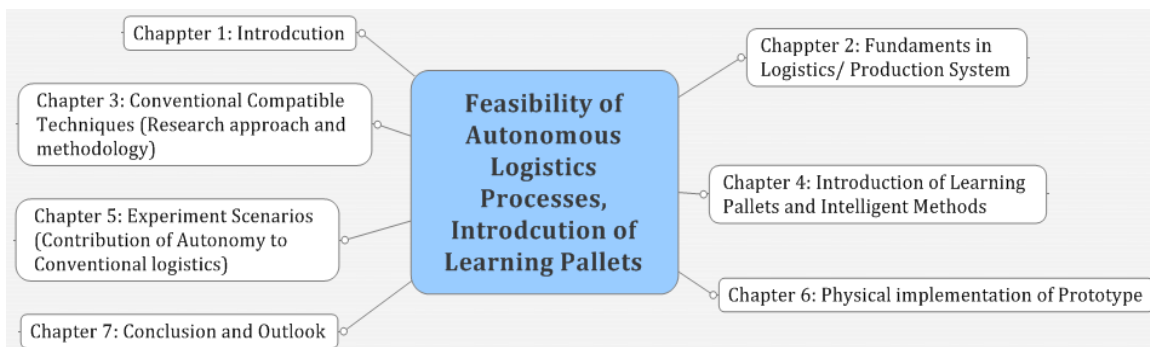


Figure 2: Dissertation navigator.

2 Fundaments in Logistics/Production System

2.1 Current Production Planning and Control

Basically, planning of operations in multi-functional systems is a crucial duty. Classical planning task proceeds with configuring a sequence of actions, so that a system is transferred from an initial situation with some preconditions to a desired situation [64]. Today, the managing and administration tasks of operations in big enterprises are accomplished by several computer-based organizing packages. Universally, these packages are known as enterprise resource planning systems (ERP) or, with more advances, advance planning systems (APS). ERP and APS are poly-functional organizing systems, which integrate the entire processes of design, planning, production, supply, and delivering, or, generally, business processes, throughout SN. In general, the current ERP and APS systems are the results of a relatively long evolution, starting from 1960s with high-volume production and assuming stable market conditions to the current highly transient market. Besides, these systems have had several successes in integrating production and business processes over industries' sections.

Basically, the master procedures in organizing and handling the performance of any production and logistics organization are carried out by production planning and control systems (PPC). In other words, the core modules of any comprehensive integrating and planning systems in industries are configured upon the outputs of PPC. Generally, PPC are integrative computer-based systems that assist the planning and scheduling of processes in manufacturing systems. Initially, the performances of PPC are founded on medium term planning, short term planning, and shop floor control, all derived from forecasted demand. Commonly, PPC are built up by six functional building blocks, i.e., data management, master production scheduling, material requirements planning (MRPI), scheduling, order release, and production activity control, see Figure 3.

Moreover, the normal procedure in PPC is to record relevant data of production in a database, besides a collection of necessary distributed information, in order to retrieve them later. At the same time, PPC employ several modeling tools for modeling business processes pertinent to planning and scheduling activities. However, solely PPC do not suffice the current requirements of manufacturing industries. This shortage stems from the specific focus of PPC which locates on production and not on other important aspects like procurement and delivery. Besides, PPC conventionally address integration and synchronization issues by means of centralized operations across a broad range of processes. Accordingly, PPC have been fostered based on a centralization and integration approach directing the business integration concept [65].

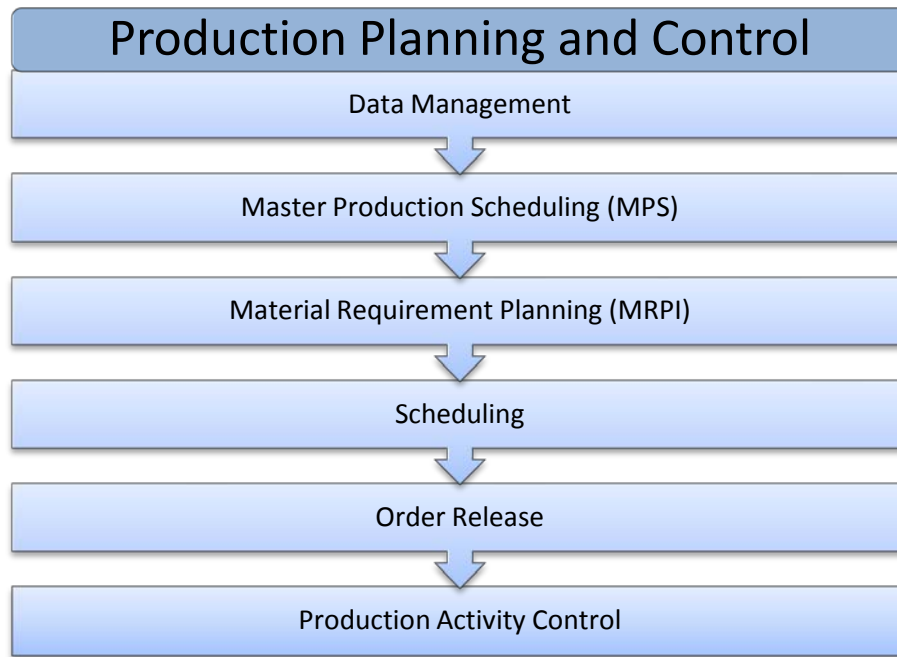


Figure 3: Functional building blocks of production planning and control systems (PPC).

In this respect, yet after the extension of conventional PPC to ERP and APS the same concept of centralized data handling is transferred to the core. Nonetheless, there are several developing studies working on this issue to adapt these systems to the current and prospective requirements, which are explained later. However, the evolution of the mentioned production and logistics organizing systems can be briefly explained as follows, see Figure 4 and for more historical review see [66].

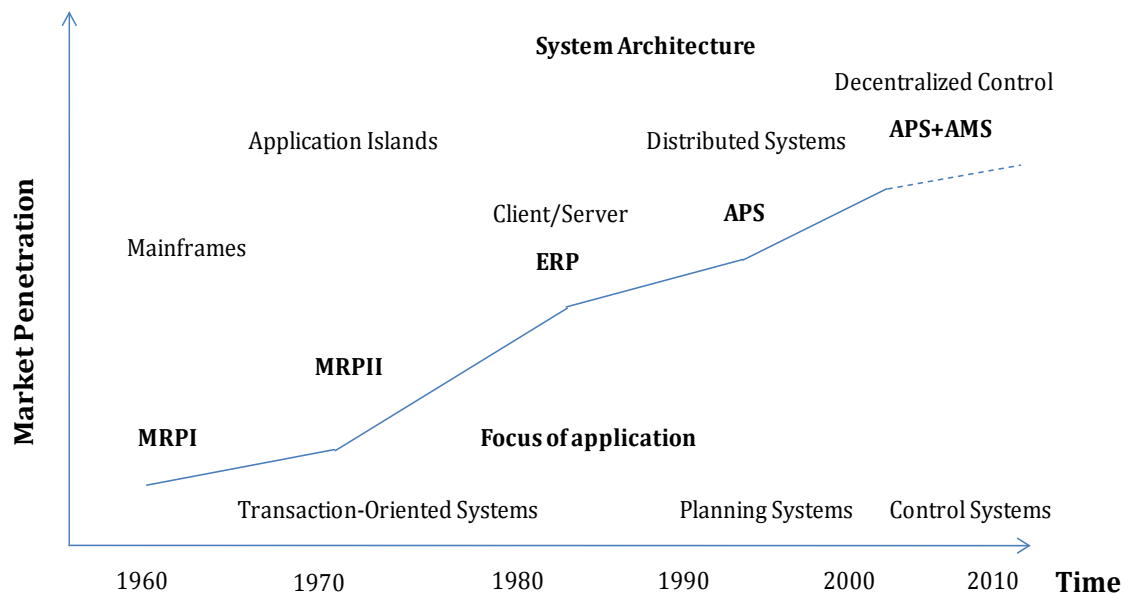


Figure 4: Market penetration of planning systems, inspired by [67].

Primitively, in the 1960s, the methods in planning and control systems just focused on inventory control by using computerized reorder point systems. Then in the 1970s, a broader systematic approach in terms of integration was introduced that generally

addressed the planning of material requirements based on forecasted demand, bill of material (BOM), and inventory status, called MRPI. Accordingly, MRPI releases an order plan in terms of net material requirements and capacity requirements over some periods based on master production schedule (MPS). In fact, this system executes manufacturing planning and control according to the inventory, ordered purchases, lead time, order lot-size, and consumptions in the respective periods. Specialty of MRPI is the distinction between dependent and independent demand in addition to its top-down calculation of requirements, see Figure 5. However, the aggregation amount of data in MRPI is located in the master (mid-short term) planning level, just one step deeper into products' parts than MPS, which releases an aggregated quantity of the required finished products in each planning period.

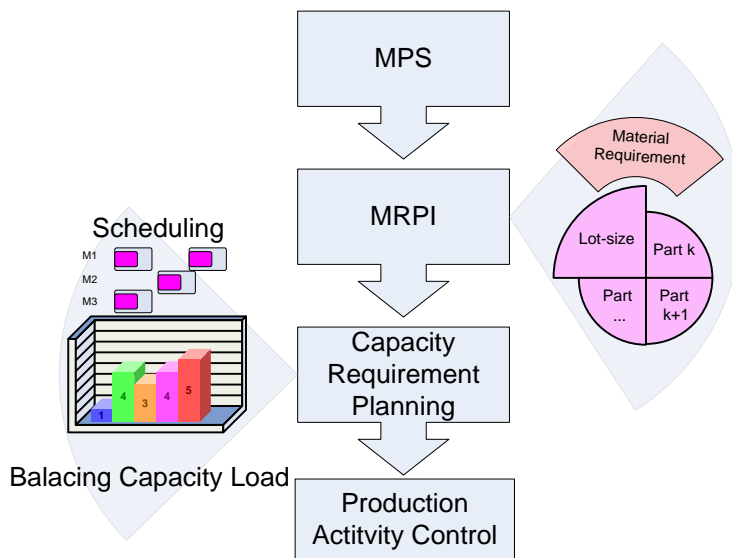


Figure 5: MRPI contribution to PPC.

In the 1980s, following MRPI an extended approach, called manufacturing resource planning (MRPII), was presented to industries, which has covered company-wide resource planning. This planning system concerns the new requirements in terms of resource capacity planning and integration of aggregated planning with job dispatching in shop-floor control, prepared for closed-loop company-wide planning usage, see Figure 6. Indeed, MRPII covers capacity planning, sales planning and demand forecasting, basic scheduling techniques, and integrates financial accounting with management functions. Commonly, MRPII consist of four main modules as:

- **Aggregate planning** that meets demand forecasting and mid-term aggregate planning.
- **Master production scheduling** that conveys basic available to promise (ATP) and enhanced master production schedule.
- **Material requirements planning** that gives planned order release, typically with infinite capacity.
- **Production activity control** that proceeds with job dispatching.

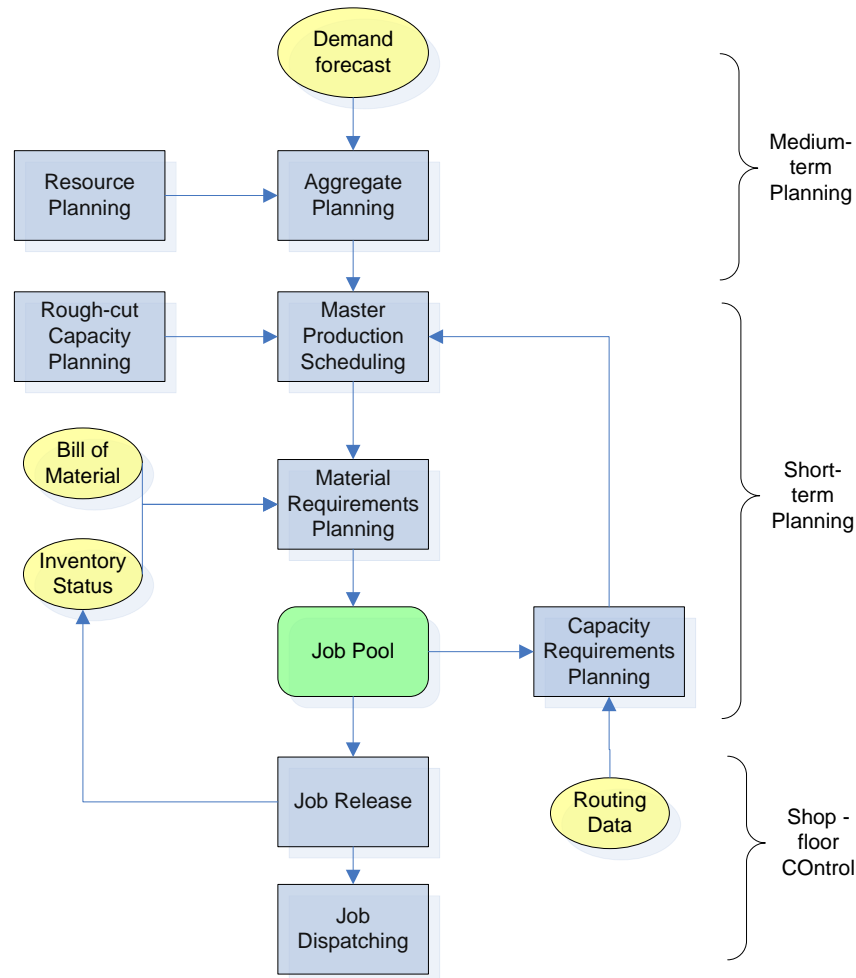


Figure 6: MRPII framework, adopted from [68] [69].

Later in the 1990s, beyond the merely consideration of manufacturing features other perspectives of integrating business operations came into account, so that CIM age was initiated. For instance, in CIM the technical aspects of products' design in addition to the planning of production processes and the quality assurance, all were considered in a broad integrating manner [65]. Following the CIM age and by improving state of the art in IT, ERP as an extension to MRPII has been developed. The term ERP was initiated by Garner Group of Stamford, USA.

Other than the functions of MRPII, ERP includes every resource planning functions over the entire business processes of an enterprise. Typically, ERP is applied as the main enterprise database that all business transactions are recorded, processed, monitored and reported [70]. In fact, ERP facilitates retrieval of information as inputs for further managerial processes of every operational section in an organization, see Figure 7. Correspondingly, a major contribution of ERP, compared to the predecessor management systems, is its integration and unification functions over all departments of an organization. However, ERP is a DSS for operative (short-term) and tactical (mid-term) organizing activities in enterprises. To some extent, ERP focus scope is located on integrating the core business

processes within a firm as well as beyond one single enterprise resource planning, which can cover planning and scheduling of suppliers' resources throughout SC. Besides, due to the over time evolution, ERP is severed as a platform for customer relationship management (CRM) and SCM [71]. Nevertheless, in order to unify ERP platforms of each enterprise throughout SC and to integrate them with SCM systems further information technology has to be employed. But the approach in ERP system is yet centralized [72] pp 315. However, the introduction of EPR has started a new age in optimizing organizational activities, see table 1 for evolutions. This popularity has begun by the R/3 product of SAP (German based company in 1994) as a complete package of enterprise systems. See Table 1 for the evolution of ERP and for more information see [68] [71] [73].

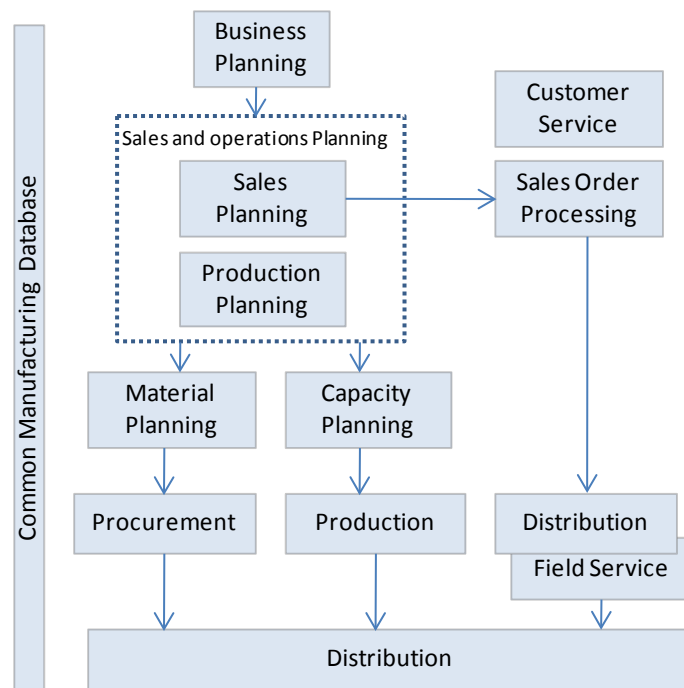


Figure 7: Information flow in ERP System [74].

Introduction of APS in the 2000s and development of them have facilitated the management of SN in a global context. Through employment of APS enterprises have been able to connect their PPC systems like ERP packages and deploy their cooperation and collaborations all over the networks. APS specialty is about optimization of logistics network operations by means of several complex and straightforward algorithms as well as integration of several production sites, distribution centers, suppliers, and customers into one unique planning model. Moreover, the algorithms encompass complex mathematical programming and simple heuristics.

Primarily, decisions making activities in all three levels of strategic, tactical, and operational in SCM are generally concerned by APS. The advantage of APS over traditional MRP systems is that they take into account availability of limited resources in practice, which is ignored by predecessors. Moreover, APS employ quantitative methodologies to analyze and support the design of SN, the production and distribution of products, and even the planning and scheduling of operations at the shop-floor level [75].

Table 1: Evolution of ERP and APS [75] [76].

| Evolving management planning systems | Components, Feature and Scope |
|--------------------------------------|---|
| Inventory management system, 1960s | Inventory control |
| MRPI, 1970s | BOM, net material requirement, MPS, inventory control |
| MRPII, 1980s | Capacity planning, closed loop feedback, sales planning and forecasting, basic scheduling techniques, financial accounting, company-wide planning |
| CIM and ERP, 1990s | Product design, process planning, quality management, company-wide resource planning, integration of business processes, shop-floor management |
| APS, 2000s | ERP Integration to SCM, optimization techniques, logistics functions integration, reporting and analytical tools, strategic management features, hierarchical planning approach |

There are several modules combined together to configure a package of APS as follows, see Figure 8:

- Demand planning and forecasting
- Supply network design and planning
- Production planning and scheduling
- External procurement and transportation planning
- Order fulfillment and ATP/capacity to promise (CTP)

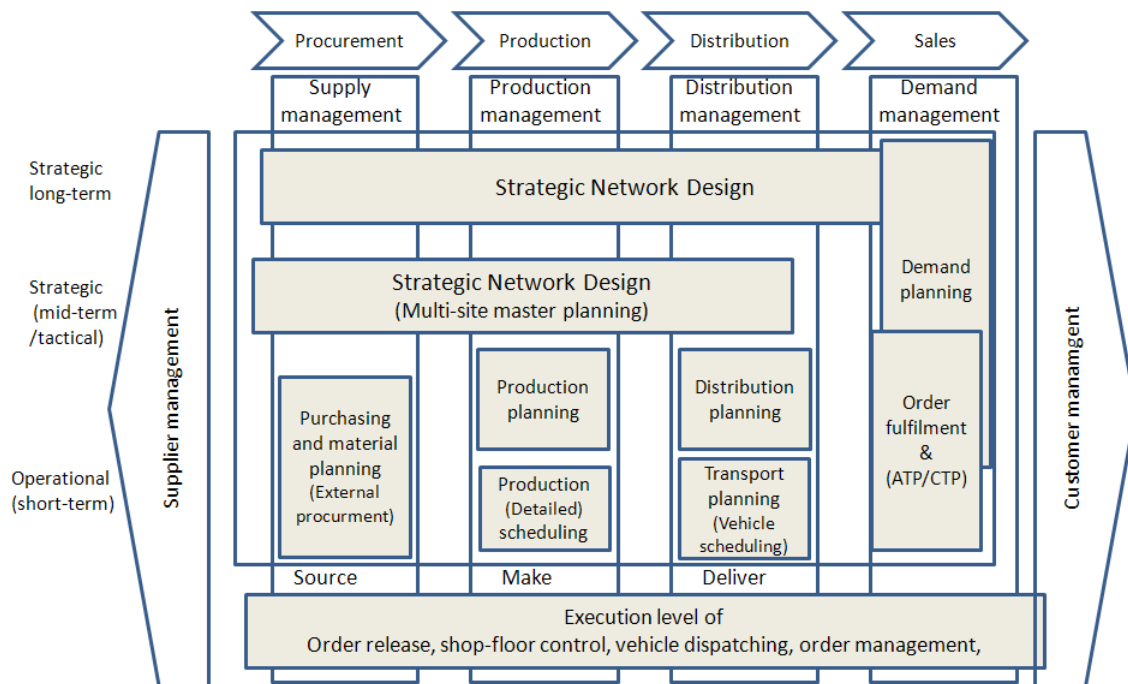


Figure 8: Categorization of APS modules and planning structure, adapted from [75] [77] [78].

After a brief introduction to the general model of PPC as well as the extended systems above that it is necessary to get a bit into the performances. In other words, it seems relevant to briefly explain the modules of APS, as the most progressed procedures in organizing SN, which are the strategic target of this research. In order to clarify the contribution of this research to the state of the art in planning and organizing operations over SN, the performance of each module in APS is opened in the following way, for more information see [75] [79].

- a) **Strategic Network Design (SND)** is a phase in APS defines the number of plants and distribution centers, location and capacity of each, allocation of product types to the plants and customers to distribution centers, and transportation routes between the nodes in a logistics network. The strategic design of SN is determined by this phase. The missions in SND can be sorted into two problems as location-allocation problem and strategic network planning. In location-allocation problem, all locations are assigned to each other, e.g., plants to distribution centers, distribution centers to customer, while vicinity and capacity are taken into account. Strategic network planning happens when an enterprise wants to redesign its supply network or expansion happens to that network. A common tool to solve this problem is the mathematical programming using mixed-integer programming (MILP) models. Since this phase reflects a strategic decision, it is rather done centrally via integration and aggregation of all strategic stakeholders in SN; thus, it has no great positional to be done autonomously.
- b) **Demand Planning** is the next step to execute advanced planning in a supply network. This phase is the only mission to be done on the three decision making levels, i.e., strategic, tactical, and operational. A reliable performance of APS is dependent on a good demand forecasting in all three levels, since the forecast is served as the main inputs to the next phases of APS. There are some tools and methods to be used for demand forecasting; among them, the outstanding ones are statistical and numerical methods [80] [81] [82], and intelligent methods like: ANN, and fuzzy inference systems [83] [84] [85]. However, demand forecasting in operational level is quite fundamental to those production strategies which produce or assemble to stock instead of to order. Although forecasting is less relevant for production strategies upon orders that resemble material pull flow, but intelligent companies follow a mixed strategy based on stock and order. Particularly, this strategy suit best to dynamic circumstances happening to final products in highly variant production systems. According to this fact, those companies try to produce their sub-assemblies to stock, regarding forecasted demands, whilst final products with customized specifications and fluctuating demands are assembled upon direct orders. This issue is profoundly discussed later as a strong solution for manufacturing companies and SN, facing dynamics in their processes.
- c) **Supply Network Planning (SNP)** is introduced as the main coordination tool in APS and integrates the modules of procurement and purchasing, manufacturing, distribution, and transportation throughout SN. Its main performance area is in mid-term level and usually has a planning period between one to twelve months, may be done in daily or weekly time bucket intervals. Its major task is to spread the forecasted

demand from the point of consumption to the point of origin in SC. This leads to making proposals for sourcing decisions, production, and distribution plans for the entire SC. Here, the network configuration is set up as well as product portfolio, production capacities per plant, storage/handling capacities per distribution centers, related costs, safety stocks, demand figures, and transportation types are defined. In doing so, SNP employs master data within an aggregated form, to tackle complexity of huge information processing. The aggregation includes time, products, and resources. Moreover, in SNP, bottleneck resources, safety stock, lot-sizing, and due date constraints are taken into account too. It is stated that optimization with a comprehensive model formulation for every transportation and distribution, plus the production plan is the prominent advantage of SNP module, as the highest advanced module, in APS. Conventionally, the tools for formulation are mathematical programming optimization algorithms. The output of SNP is a generic model formulation of rough-cut planning, which is capable of being modified manually. Generally saying, SNP module is a potential level of APS to be accomplished by collaborative executions within distributed style. However, decentralization of decision makings depends on the level of information exchange between the engaged entities in SN.

- d) Production Planning and Detailed Scheduling PP/DS** is the direct module after SNP to identify a feasible production plan and schedule for each individual plant. The planning horizon is typically between one week and three months, while the scheduling horizon is normally from one day to two weeks in different production environments. The main difference between PP/DS module and SNP is its continuous time capacity in planning and scheduling besides using detailed master data, contrary to time buckets planning intervals in SNP. Generally, this part of APS is the most time consuming and complex module, in terms of calculation and revisions (updating), regarding the variety and complexity of production systems. For instance, each scheduling problem has its own algorithms to solve the problem. Here, every detailed data about production, e.g., availability of finite resources, capacity, set-up time and sequencing, material flow routing, time-phasing, as well as customer demand, e.g., due date limitation, are taken into account. Usually, PP is carried out prior to DS in such a way that the quantities of production are defined with infinite capacity, based on modification of SNP outputs, to fit supply with each plant's demand, like MRPI. Through the PP process dependent material requirements (components of final products) regarding BOM are identified and lead times are calculated by available hours of resources, routings, and processing times. Here, an estimate about the feasibility of the plan is given by use of backward planning, started from due dates (given by customer) with unlimited capacity. Then later DS generates changes in terms of start and end dates, the sequence of operations, and possibly resources, to meet real-world capacity constraints. There are some common scheduling objectives taken by DS as minimization of set-up time, Lateness/tardiness, cycle time, and makespan. Changing quantities of production orders or shifting them are the tasks of DS to achieve a feasible plan. Accordingly, each scheduling problem, i.e., single machine, parallel machine, job-shop, flow-shop, and

open-shop, may have different objectives, see [86]. For the sake of simplicity and in order to reduce the calculation time, conventionally, simple and universal heuristics, e.g., genetic algorithm, simulated annealing, tabu search, constraint programming, are employed by this module, rather than sophisticated algorithms like the shifting-bottleneck. This subject is later more discussed in scheduling section. However, generally, the main objectives of PP/DS include minimization of work-in-process (WIP) and stocks, minimization of set-up time/cost caused by sequences, maximization of resource utilization, and meeting due dates (objectives in logistics). Besides, the main outputs are production orders to meet customer orders. In literature, it is mentioned that because of limited scope of PP/DS and requirement of detailed information in short-term horizon, compared to SNP, modern PP/DS module is preferably occurred in a decentralized manner. Thus, this module of APS is the most potential possessor in getting executed autonomously within heterarchical structures and decentralized formats.

- e) **External Procurement** module is applied to select suppliers, define purchase quantity and propose purchase orders. The outputs of DS are directly used by this module in order to distinguish critical products with long lead time, supply restrictions, or priority in production. Decision over purchasing or producing a component in-house, according to its cost or other factors, is done in this part of APS. Procurement of required materials can even include some manufacturing steps of corresponding components which the production orders of them can be issued internally as well as externally by this module.
- f) **Order Fulfillment and ATP/CTP** has the main role in determining feasible fulfillments in responding to customer orders. There are two major modules in this part as ATP and CTP. The ATP module always checks the current stock and planned receipts for meeting new ordered demands, while, in addition to ATP, CTP looks for availability of production capacity in already issued (planned in PP/DS) production orders or extra capacity for issuing new production orders. However, in push flow systems, e.g., make-to-stock (MTS), ATP beside CTP module makes more sense than other pull systems, e.g., make-to-order (MTO), that CTP is more meaningful. Generally, by evolving a new customer order the type, the amount and due date of that are taken and observed by the ATP procedure. If the order specifications are matched with the available stock, then the order is committed, otherwise, it goes through the procedure of CTP to check the capacities with the corresponding specifications. In this case if the requirements are met, then the commitment is executed, if not, then the order is put to the next optimization run in DS. ATP and CTP are the modules with already negotiation-based background, which inventory and production sections are engaged in. They can be run on local facilities as well as global networks. Moreover, manipulations of orders, concerning the accepting, rejecting, shifting, taking from other storages, or splitting them, are accomplished in this section. Decision over proportion of products to be distributed between centers is done here. However, the notion of ATP procedure is already defined before by MRPII. It is noticeable this module can be enhanced by means

of increasing flexibility in manufacturing systems through autonomous objects as well as control.

- g) Transportation Planning and Vehicle Scheduling (TP/VS)** module plays a crucial role in logistics operations. For example, proposals for distributions and replenishments of goods/materials are issued by TP/VS. In fact, the definition of transportation means and distribution network, distinction between own-served logistics operations and external service providers in long term decisions, design of transportation routes, transport quantities/frequencies and optimum utilization of these resources in mid-term level, as well as determination of delivery routes, allocation of loads to transport means, and daily shipment quantifies in short-term decisions, all are covered by this section. There are several constraints which must be taken into account specifically in short-term decisions over VS. Among them are time windows for delivery, vehicles' loading capacities and types, route start and end points, which are applied to minimize the travel length or time. However, VS module employs directly different variants of vehicle routing problems (VRP) to solve diverse aspects of VS in practice. In addition, there, some new trials to adopt decentralized problem solving in this branch of complex problems, e.g., distributed logistics routing protocol (DLRP) [87]. This module in APS is one of the most potential modules for employing autonomous control in a decentralized manner. However, it is not covered by the current study.

In conclusion, the development of advances in planning systems along state of the art in ICT, specifically the internet, is strengthening the concept of collaborative planning based on the internet in APS [88]. Recently, the collaboration approach has raised a great research interest in this field, which connects the conventional performance of APS to the distributed and decentralized decision making throughout SN. This pushing forward functionality of APS links the topic of the current study to the real-world oriented practices, in organizing and managing operations across SN and manufacturing enterprises.

Furthermore, it can be argued that the core concept in the evolution of planning systems has been accompanied with an intention towards integration and unification, by means of central monitoring. This has held true from the development of MRPI to CIM and from there to ERP, and partially to APS. In other words, all of these systems conventionally follow a hierarchical structure that on the top level of the hierarchy highly aggregated data supports the strategic decisions [77] [89]. In contrast to that, by moving towards lower levels in the hierarchy, decisions are disaggregated into detailed information [77]. This hierarchical integration framework has achieved several advantages in optimization and, to some degree, in the required reliance, for a long period. However, this approach does not fully comply with the requirements of the in progress as well as future transactions between production sections and organizations. So, the pure planning and scheduling outputs of this framework show some deviations from current capacity; because the framework has some presumptions that are not always true in practice.

Accordingly, there are several reports about the incompetency of mid- and short term planning and scheduling outputs, done by these hierarchical systems, with practical operations. For example, any real-time changes in running operations or other evolving events are conventionally neglected by the hierarchical planning structure of such systems. This leads into some uncertainties in operational levels. Likewise, these limitations are mostly announced in production scheduling problems, where the real constraints of the problem cannot be fully seen on time. Kreipl *et al.* [79] claim this fact in their relatively comprehensive description about planning and scheduling of SC as well as APS. They directly mentioned that unstable (dynamic) environment, e.g., machine breakdowns, sudden demand fluctuation, backlogs, may cause inconsistencies in scheduling embedded in the current structured APS. To address the reason of these discrepancies, it can be highlighted that they all return to the planning structure of these information and planning systems. The top-down planning procedures of such systems cannot practically reflect every constraint of the real-world into the planning procedure, whereas by means of a bottom-up approach, the constraints can come closer to the real-time states of production systems. For instance, to illustrate the hierarchical structure of these systems, detailed production scheduling in APS can be only released after aggregated outputs of production planning in a higher level of planning hierarchy [79]. This easily emphasizes the top-down problem-solving approach of these decision support systems (DSS) for production and logistics.

However, recently, some researchers have challenged the concept of centralized integration of all processes across the sections in enterprises of SN [89] [90]. Correspondingly, the top-down data expansion over this integration approach causes imprecise detailed planning in practice. This fact is specifically addressed in short term planning and detailed scheduling tasks. Therefore, in the latest developments of APS, as an alternative to the standard ERP and other planning systems, some literature refers the information flow to bidirectional flows instead of top-down flow. This contribution leads to an interactively development of closed to practice plans [90] [91].

Inspired by the paradigms of self-organization as well as autonomous cooperation and control, integration of all processes in a system, in order to make a generic plan, has changed its place with cooperation of autonomous agents to make a common plan. Here, the agents are responsible for making local plans and decisions by and for themselves. This concept is gradually deploying itself in managing and organizing systems, so that it is affecting the structure of APS as well. However, with regard to the targets of self-organization— beyond the state-of-the-art— it can be argued that integration of all processes across complex SN is an incompetent methodology. In this context, each self-organized module in a complex system must be able to make its own plan and decision regarding its perspective to the environment. However, this concept is still far from the practice (as an absolute functionality) and is not covered by the scope of this research too, since the concern of this study is about the pragmatic industrial requirements and the feasibility issue. Correspondingly, this study suggests that the strategic and, to some extent, tactical planning operations have to be executed based on the overall performance of SN

against the market changes. This is a common and logical performance in such cooperative and collaborative networks, since a universal strategy is needed to coordinate the operative units within an organizing system. The best evidence of this fact is the biological swarms like ant colonies. Whereas every member of the colony is autonomous in its decisions, they follow a common goal for the society [92]. Now, for instance, if each member of a supply network defines its own objectives, then the emerging targets with conflicts lead the entire system into chaos. On the other side, employment of autonomous control in operational levels seems a feasible solution as stated by several conducting studies in this field. This holds specifically true when the real-time decisions play a crucial role in configuring operational level activities.

Fortunately, the integration concept in ERP and APS systems, in general, shows no significant contradiction to the new approach of decentralization and distributed control over networks of cooperative and collaborative operations. Indeed, the integration concept can easily adjust itself with the autonomous control, to some degree. It is recommended that the autonomous control is rather suitable for the operational planning level in the current practices of information and organization systems. This claim is partially experimented in this study. However, in general, decentralization of the planning and control task is the generic target of autonomous system and respectively any self-organized system. Idealistically, the goal is to configure a fully heterarchical structure for such systems in a way that each stakeholder of SN with heterogeneous objectives is able to make its own decision by freedom. However, since planning and control systems are dependent on strategic decisions the level of autonomy is always relatively defined and has several limitations in the practice.

Finally, in literature, it is discussed that within a decentralized decision-making environment there has to be some coordination factors at certain levels. Sometimes coordination between plans or decisions of every member in SN may result in infeasible or non-optimum solution for SN. Nonetheless, some other concepts exist without leading into coordination of all members in any way. Thus, the coordination subject is like a spectrum, which may vary in various circumstances. However, in academic papers, it is often referred that some aggregation level of data between decentralized decision makers is required with still *centralized coordination* [37] [88] [93]. In order to clarify the definition of centralized coordination it is enough to mention that the respective coordinator has the information about all collaborative parties to be coordinated. This coordinator is centrally operating and monitoring, although the single decisions are made in a decentralized manner.

2.2 Logistics and Supply Chain Management

Today, the current market situation and intensive competitions, scarce resources, globalization, and the need for the supply of the right product to the right customer within the right time and with the lowest cost, force companies to manage their supply networks as well as optimizing their own processes. Generally, it is agreed that no isolated company in the current business environment exists that can be successful in the market. Instead of

working like an island, industries prefer to cooperate within supply and delivery networks, from upstream to downstream. This fact has necessitated a holistic integration approach between members of SN. Respectively, as a prominent competitive advantage, this integration and coordination aim has obliged the phenomenon of the supply chain management (SCM) across the members of networks [48]. By concentrating on the logistic processes and transportation in SN, SCM can be particularly translated as an integrated management approach of logistic processes. In this manner, the main focus of SCM is located on the issue of inventory reduction both within and across SN [94]. In this section, the common definitions and the general relationships between both terms of SCM and logistics are described in details.

Basically, the definitions of logistics and SCM are mutually dependent, so that logistics is sometimes assumed as a wider field, encompassing SCM (mostly in Europe), and sometime else this affiliation is vice versa (usually in USA). In other cases, the two terms are similarly treated and alternatively used. For instance, Cooper *et al.* [95] define SCM as the integrating mission of all business processes from final customers to initial suppliers. This duty results in the provision of products, services, and information, by bringing added value to customers. In addition, the concerned business processes include planning, implementation, and control of inventory, as well as material and information flow. In their conclusion, several components are recognized for SCM as: planning and control, work structure, organizational structure, product and information flow, facility structure, product structure, management methods, power and leadership structure, risk and reward structure, culture and attitude. Moreover, the Encyclopedia Britannica defines logistics, according to the Council of Logistics Management in USA, as “the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from the point of consumption for the purpose of conforming to customer requirements”. Indeed, the two definitions define the close dependency of both expressions. Accordingly, from the academic perspective, Günther [75] regards SCM as a multi-disciplinary field of research with contributions of various scientific disciplines, such as management, industrial engineering, logistics, operations research, and business computing.

Christopher in his book [7] defines SCM as “the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a Whole”. In his definition the relationships, the added value, and the cost are particularly highlighted. Additionally, he connects the definition of SC to SN by extending the structures of SC. In the work, a supply network is described as interdependent and connected organizations working in a mutual and cooperative context to control, manage, and improve information and material flow from upstream to downstream (in the vicinity of end customers) of the network. However, apart from the structural discriminations between SC and SN the terms are alternatively used throughout the current study.

In the book of Coyle *et al.* [96] logistics is introduced as a broad management concept, which adds inbound logistics to outbound logistics of material distribution. They describe logistics as “the process of anticipating customer needs and wants; acquiring the capital, materials, people, technologies, and information necessary to meet those needs and wants; optimizing the goods (or service) producing network to fulfill customer requests; and utilizing the network to fulfill customer requests in a timely manner”. However, in their work, SCM is seen broader than logistics activities. In their consideration logistics activities comprise: transportation, warehousing and storage, packaging and material handling, inventory control, order fulfillment, demand forecasting, production planning and scheduling, procurement, customer service, facility location, return goods handling, parts and service support, salvage and scrap disposal. Furthermore, logistic operations are generally classified into two main groups as: inbound logistics and outbound logistics. The inbound tasks cover the activities of demand forecasting, purchasing, requirement planning, production planning, manufacturing inventory, warehousing, and material handling. Accordingly, the outbound logistics may cover finished goods inventory, distribution planning, order processing, transportation, and customer service.

Harrison *et al.* [97] claim that logistics and SCM are often used interchangeably. However, they believe logistics is a subset and enabler of SCM. In the work, supply chain is inherently considered as a network of partners working collectively together in order to transform a simple commodity in the upstream of a supply chain into a final product in the downstream, which is valued for end users. In the meanwhile, the management of returns is done by the partners at each stage. Accordingly, they define SCM as “planning and controlling all of the business processes— from end customer to raw material suppliers— that link together partners in a supply chain in order to serve the needs of the end customer”. They explain logistics as coordinating processes for material and information flows throughout SC. Tan [98] in his paper express SCM as a holistic and strategic approach to logistic operations and material management. He traces the evolution of SCM from purchasing and supply activities to transportation and logistics with emphasis on integrating, streamlining, and visibility of operations, besides the cycle time reduction. Moreover, Monczka *et al.* in [99] pp 9 obviously state the interchangeability of SCM and logistics. They describe logistics according to the definition of Chartered Institute of Logistics as “the time-related positioning of resources, or the strategic management of the total supply chain”. Furthermore, Croon *et al.* in [11] made a general literature review about the terms and related topics of SCM.

Naylor *et al.* [100] describe supply chain as a system whose constituent parts include material suppliers, production facilities, distribution services, and customers, linked together via a feed-forward of materials and feedback flow of information, including the flow of resources and cash through the chain. According to Moyaux *et al.* [101] a supply chain is a set of autonomous business units that producing and distributing products from downstream to upstream. It is noticeable that SC are normally arranged as series of suppliers, manufacturers, and distributors aligned in a linear and successive order. Nonetheless, SN address those members of SC that configure networks of suppliers,

manufacturers and distributors via virtual interconnections [48]. Figure 9 defines an exemplary supply network with the generic activities in each echelon of that.

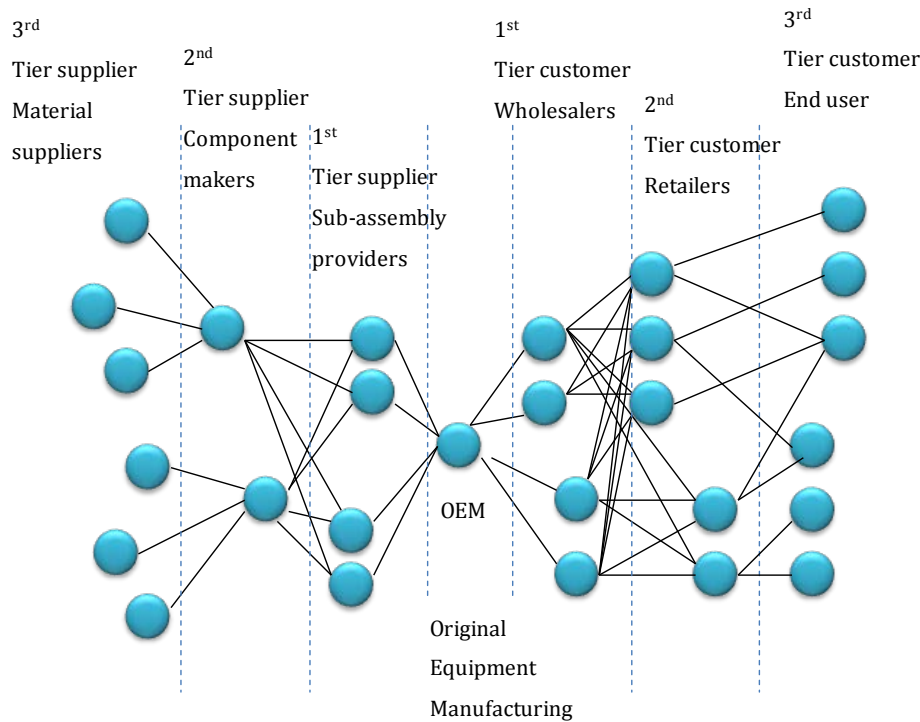


Figure 9: An exemplary conventional supply network with each section's duty, adopted from [99].

Conclusively, from the literature review, it can be comprehended that SCM normally integrates the marketing, the accounting, and similar staff activities, into operational processes, which can be exclusive for SCM. On the other hand, logistics solely complies with operational processes and pays less attention to marketing or accounting stuffs. Therefore, SCM may cover a wider scope than logistics. However, since the purpose of this work is not to deal with the definition of such terms, but the content of processes, without entering into staff activities, both logistics and SCM are uniformly treated.

In most of the reviewed definitions, it can be perceived that time, value adding, and cooperation of business processes are reflected as the specifications of SCM and logistics. Thus, it is crucial to put the focal work of research on these issues and improve them accordingly. It is noticeable that in this work, the processes of both terms are summarized in the tasks to be done by APS, which is widely explained in the previous section, see **Fehler! Verweisquelle konnte nicht gefunden werden..**

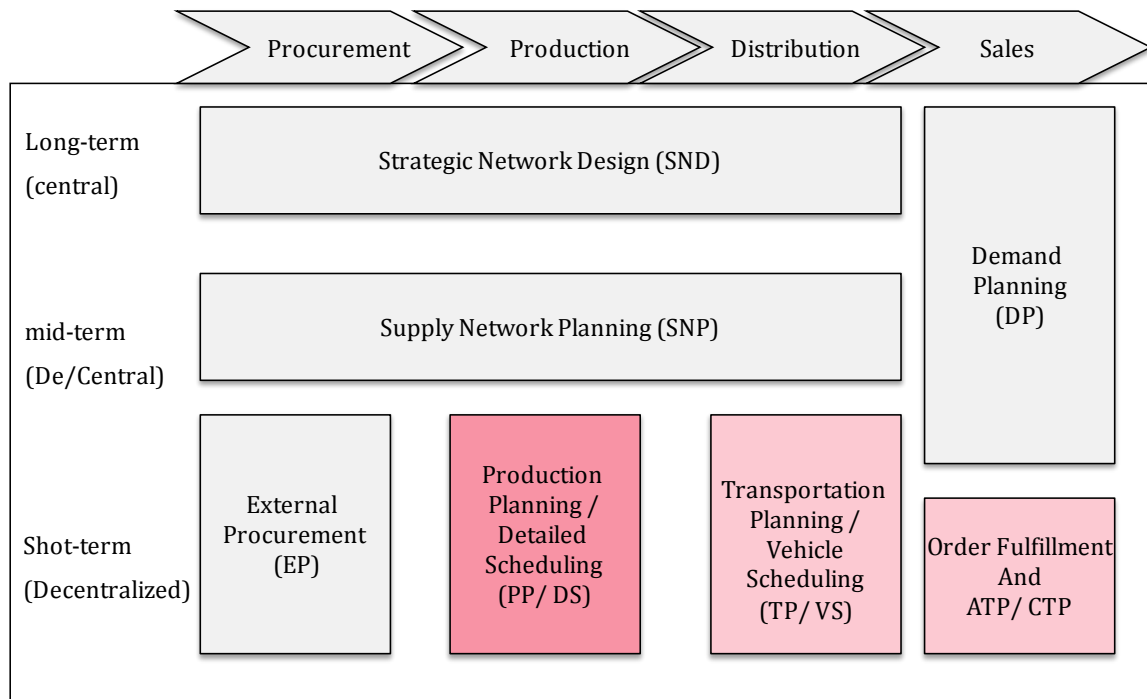


Figure 10: Classical APS with respect to implementing potential of autonomous control system, adopted from [75].

2.3 Dynamics and Autonomy in Logistics

2.3.1 Dynamics in Logistics

Originally, the term of dynamics has several aspects in the current manufacturing industries; each of which sometime needs a unique and other time a generic solution. There are several points of view that the dynamics can be interpreted by. However, from logistics and production point of view dynamics may be any kind of changes, impediments, and unexpected events, which happen to a stable system (in steady state). Among all incidents, just some causes and effects of existing dynamics in logistics and production networks can be listed as follows. For more information see Sabri *et al.* [102] and Tian [103].

- Rising, fluctuating, and turbulent demand.
- Product customization (product diversity).
- Ascending and non-implied customer requirements as well as rigid expectations in terms of right product at the right time, location, and quality.
- Globalization in supply and distribution, as well as narrow competitions.
- Market and demand uncertainties, technological changes, changes in suppliers' reliability.
- Redundancies (which create time and gap).
- Complexity in operations, regarding non-linear dynamical models in planning and control.
- Adaptability (need of pro-/re-activity).
- Bullwhip effect, emerging and shifting bottleneck (due to the product variety).

- Overloading, urgent orders, and under capacity production (unplanned utilization).
- Machine downtimes, defective production and equipment.
- Fluctuation in leveling and sequencing, mixed production and stock deficit.
- Lack of awareness about all details and process deficits.

These all easily show the value of a robust supply chain as a competitive advantage, while having smooth material handling and information sharing across the chain under dynamic circumstances. In doing so, some metrics in evaluating the performance of SC with dynamics can be considered that some of which are following:

- Product life cycle (introduction, growth, maturity, saturation, decline).
- Product differentiation and characteristics (modularity, life cycle, fashion, transient, etc.).
- Demand situation-attributes (volatile, constant, seasonal, stochastic, etc.).
- Market situation (competitors, best practices, business excellence).
- Production strategy (make-to-order, make-to-stock / built-to-forecast, engineer-to-order, assemble-to-order).
- Technology competency (cost, state-of-the-art, effectiveness).
- Product mix and volume (lot size, sequencing, leveling, balancing).
- Customer specifications (loyalty, due date, lead time, etc.).

Over the recent decades several methodologies have been introduced to industries in order to handle the evolved dynamics. For instance, from dynamics in logistics/production point of view, most of the developed methods have been working on flexible, agile, reconfigurable, liable, and responsive (manufacturing) systems, to overcome the dynamics [104] [105] pp 2. However, the earlier methodologies were considerably trying to resist against any troubles made by dynamics in systems' behavior and to alleviate their ominous symptoms. This was conventionally preferred rather than using dynamics as competitive advantages for own businesses. However, according to Scholz-Reiter *et al.* [54], it is believed that two types of treatments can be used in challenging dynamics and changeability in the logistics/production environment. These include the strategies to compensate and reduce dynamics in logistics as well as the strategies to adopt dynamic behaviors into own operations, to adjust own performances to the changes, see Figure 11. On the one side of this figure, the autonomous control and objects are considered as competitive advantages, by adopting flexible decisions in facing dynamics. In contrast, the effects of dynamics are considered undesirable on the other side of the spectrum and have to be tackled, e.g., by the goals of lean manufacturing.

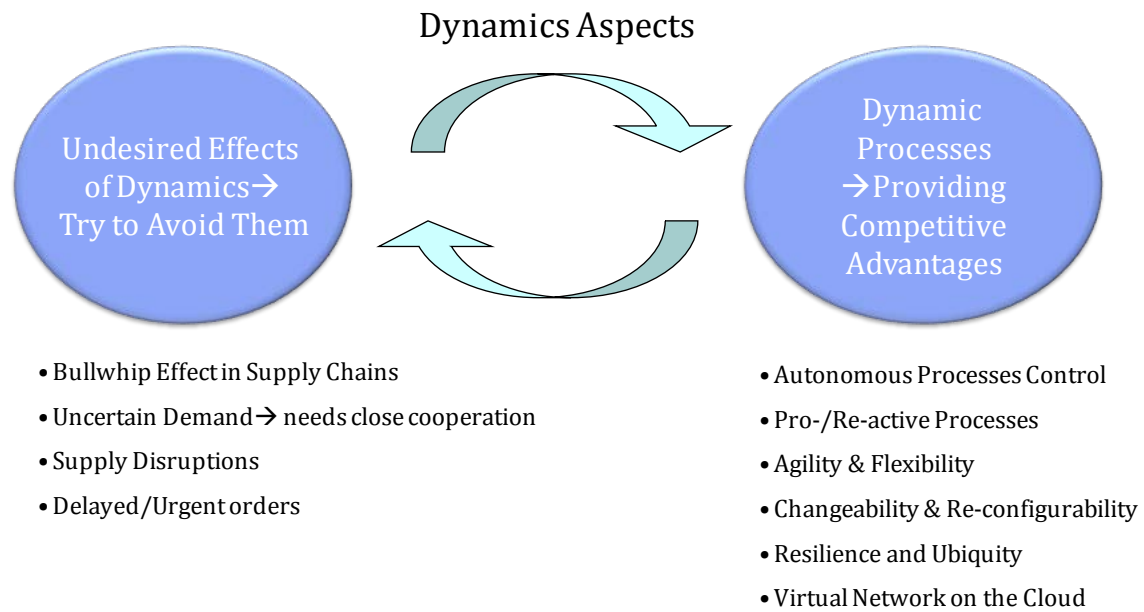


Figure 11: Aspects of dynamics in logistics and manufacturing systems.

Accordingly, for a long time it has been sought for advanced strategies in logistics and SCM to transform uncertain nature of business environment into opportunities and competitive advantages, stated by Yang *et al.* [106]. They raise this issue concerning the uncertainty in logistics, among the other existing dynamics. According to them, uncertainty is treated as the difference between the amount of required information in dealing with a task and the available information for accomplishing that one. In their work, uncertainty is expressed in company with complexity, dynamism, volatility, unpredictability, stability and diversity, variability and heterogeneity, as well as lack of hierarchy. Thus, these issues need to be treated in dealing with dynamics in logistics.

On the other hand, the novel autonomy paradigm in logistics tries to adopt the dynamic nature of production and logistics environment into its own performance. In this respect, for example in the 2000s, the concept of AMS have been emerged to accomplish production and inbound logistics operations, following several manufacturing systems like FMS and RMS [54] [107]. In general, this autonomy is reflected in a heterarchical control structure with the aim of approximating the decision-maker elements to products and equipments, while considering the capabilities of IMS, HMS, MAS and other compatible manufacturing system. Indeed, the introduction of AMS was along with the appeals of systems' progression in terms of more compatibility, flexibility, and adaptability versus more dynamics in logistics [52].

In a wider scale, it can be argued that integration between all members of SN— as the conventional aim of SCM— brings about higher complexity in terms of coordinating all processes. Simply, covering and coordinating every effective process of a supply network burden tough monitoring and controlling duties to the central controller of a network as well as to the entire network. On the contrary, by shifting from the conventional concept of SCM about intra-/inter-organizational integration, the further approach has been evolved.

According to Windt *et al.* [108] the move from central planning systems towards decentralized control with real-time decision makings and high flexibility is a proper solution for handling highly dynamic and complex systems. Basically, the autonomous and decentralized systems are expected to create a well-behaved network in facing uncertainties (dynamics) by reflecting a satisfactory responsiveness, limited oscillatory behaviors, and robustness, see Duffie *et al.* [109]. However, Scholz-Reiter *et al.* in [110] discuss about autonomous logistic processes according to the level of autonomy and the requirements for implementing such novelty in practice.

Contrary to the conventional systems, the autonomy, as a new approach, has no intention for integrating and coordinating all effective units of processes across networks. Nevertheless, since the units are free in decision making, it aims at coordinating the processes just at the interfaces, to get a global consistency. In the current study, this approach is reflected as undertaking the autonomy in operational control level and then embedding some tolerances in the centralized tactical planning level. In this policy, the members or units of a supply network autonomously deal with their own internal processes [111], whilst their strategic and tactical decisions are made centrally in an integrated manner. By means of this approach, the complexity of the coordination task across a network get easily reduced, whereas the flexibility of local operators can be increased in confronting with uncertainty and dynamics [48]. In summary, autonomous control systems have some prominent features in literature as: decentralized and distributed control and decision making configuration, self-organized, and heterarchical structure. These characteristics clearly discriminate the autonomous systems from the conventional ones with hierarchical and centralized structures. These specifications are generally explained in the following.

2.3.2 Centralized, Decentralized, and Autonomous Control Systems

According to the definition of the online Business Dictionary [112], a system is “an organized, purposeful structure regarded as a whole and consisting of interrelated and interdependent elements (components, entities, factors, members, parts, etc.). These elements continually influence one another (directly or indirectly) to maintain their activity and the existence of the system, in order to achieve the goal of the system”. In this regard, interrelation, elements, and goal of a system are specifically emphasized. Thus, studying these highlighted aspects in any systems is essential. Generally, elements of a system may have different interdependency and interactions with each other that leads to different structures. Additionally, inspired by [113] [114], defining the structure of a system is a matter of control, authority, hierarchy, heterarchy, decision making, interactions, individualism and collectivism, homogeneity and heterogeneity, and uncertainty. For instance, van de Mortel-Fronczak *et al.* [114] believe that control systems with hierarchical structure are very complex, difficult to maintain and modify, and highly sensitive to failures, when the systems grow in scale and scope. In contrast, heterarchical control systems are flexible, modular, simply modifiable, and to some extent, fault tolerant, see Figure 12. However, regarding these specifications, there is no unique definition in literature for different structures of systems. There may be several overlapping

expressions that each reflects the mentioned specifications for the structure of a system, from different points of view.

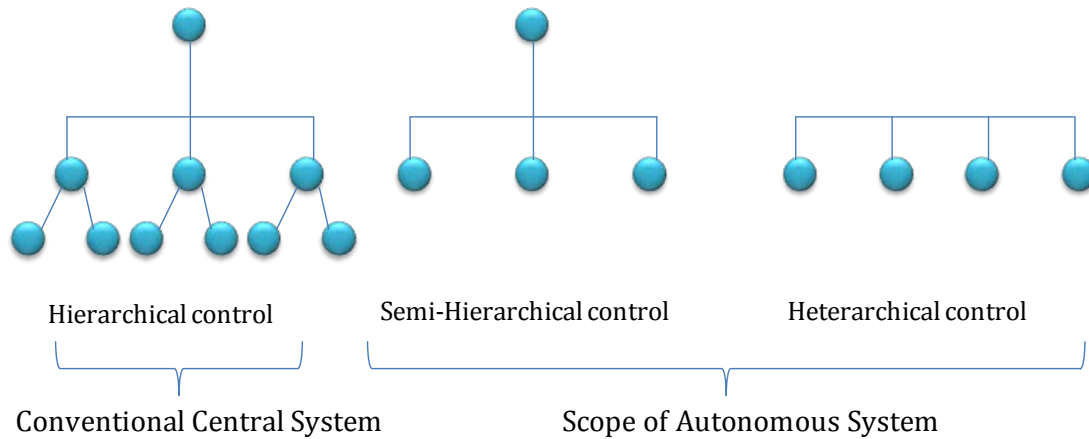


Figure 12: Control structures with autonomy domain interest, according to [114] [115].

Basically, a system regarding its structure can be classified into centralized, distributed, decentralized, and autonomous system, according to Jaffari [116]. A central(ized) system refers to a system with one central entity who has the authority to receive data from other entities and takes decisions over that for every unit [117]. This central entity within a hierarchical structure is called supreme or master in different disciplines [116] [118]. Obviously, the control structure in such a system is hierarchical, in contrast to the decentralized and autonomous systems with heterarchical control structures. According to Matsumoto *et al.* [119] in robotic, a central system is explained by a host controller to process and control all devices, which are connected together. Moreover, they explain distributed systems as distributed controllers with embedded computers that are connected to a supervisory computer, which only monitors the general condition of the working environment (use of local control and central management), see Figure 13. Nevertheless, they distinguish between distributed and decentralized systems; for a distributed system, they assume a certain supervisory computer (a center), which has the responsibility for the whole work of the system. But, in decentralized systems there is no necessary supervisor to be equipped and the whole work can be accomplished in the form of decentralized sub-tasks by distributed robots.

From the work of Ahituv *et al.* [120] it can be understood that a centralized system is a system with realizing all decision makings in one centre, and all computing capabilities are concentrated in that point. Similarly, a distributed system is like a common network, but with a deployed (distributed) computing capability. Eventually, a decentralized system is like distributed systems with the deployed computing capability in various locations, while the computing units are not linked within a common network. Accordingly, a decentralized system inherits the distributed system' characteristics.

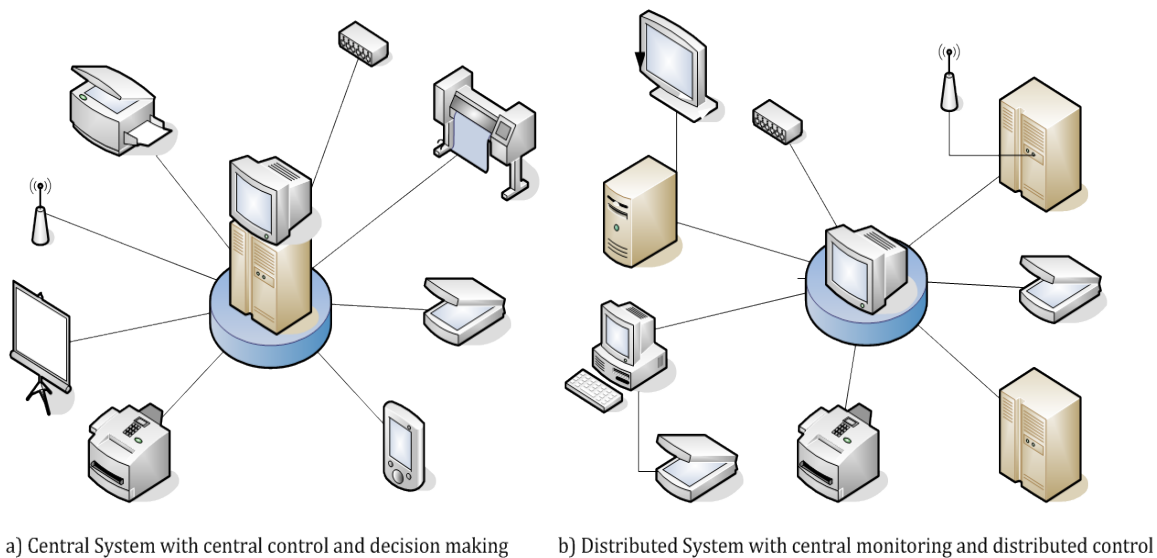


Figure 13: Exemplary central and distributed systems in technical systems with star connection.

Regarding the work of Kumar *et al.* [121], in a decentralized system, with decentralized control, a collection of local (decentralized) decision makers interact with each other and eventually come up with a global decision. They mention that distributed systems can be reduced to decentralized systems in such a way that the mean of communication among local decision makers can be eliminated. Additionally, in this context each decentralized decision maker must have an assessment mechanism for self-ambiguity. However, it can be argued that not always a distributed system can encompass (be reduced to) a decentralized structure.

Furthermore, Meyer *et al.* [122] in their study over human resources in Europe define the decentralized systems with frequently hand in hand decision makers with increasing management autonomy to improve the performance of the systems. Besides, the decisions are closed to the points that require any decision. On the other hand, the authors raise the issue of accountability for central systems. Additionally, it is mentioned that decentralization brings heterogeneity to systems. The authors conclude that when the desire for avoiding uncertainty in human-resource systems is high then the degree of decentralization is low, and vice versa.

However, distributed and decentralized systems may be incorrectly considered equivalent in some applications. Although both systems have some coherent features and contributions, but they are not similar in their performances. For instance, a central decision making system like, ERP system, can have several topologically-distributed entities that cooperate in making a decision, but the decision is made centrally after receiving the required information from distributed entities. On the other hand, a decentralized system can be a collection of independent decision making entities that make their own decisions according to their local atmosphere and possibly based on the collected data from other entities, like a multi agent system. However, since a decentralized system is yet assumed as a uniform system, there must be a common goal, besides other local targets, to be desirable for distributed entities. This simple example illustrates the

difference between both attributes. The information and data are intentionally used in this example to show the contribution level of distributed entities in a centralized system, which can transform data to information, while the final decision is made centrally.

Eymann *et al.* [123] point out the drawbacks of central systems and moderately introduce the motivation of moving towards decentralized systems. According to them, a central system is not proper for dynamic environments. They highlight the requirement of having dynamic, fast changing, and flexible systems. Additionally, coordination in central systems requires a global knowledge over the state of the system (or network), and is subject to time lags and, depending on the scale of the system, may lead to long latency times. Moreover, they challenge the central collection of data and central allocation of tasks. Alternatively, they advocate the decentralized coordination in systems with real-time control and harmony with various calculation capacities. This decentralization has to be achieved through the application of autonomous and decentralized devices, which employ constant negotiation, as agent technology, to get consensus. They may use machine learning mechanisms to adapt the decisions of autonomous objects, with the purpose of achieving a co-evolution between software agent strategies and self-regulating coordination patterns.

Generally, autonomous systems address those systems with intelligent and flexible reactions against changes in operating conditions and demands, coming from the environment. According to Rehtanz [124] the origin of autonomous systems, at least in technique, refers to the robotics branch. He considers some fundamental components for any autonomous system. The components include target or inquiry as input, as well as three functional layers as the management and organization layer, the coordination layer, and the execution layer to interactively work together. Additionally, he considers two components for such systems, a data-acquisition component, as the only interactive component with the environment, and information-base component to make a knowledge base on data acquisition. The information-base component is bilaterally in cooperation with the three functional layers. However, in addition to the mentioned characteristics for autonomous systems, they have some general characteristics as: self-decision making, self-organizing, distributed and decentralized control, and heterarchical structure, see Figure 14. These specifications are elaborated in the following sections.

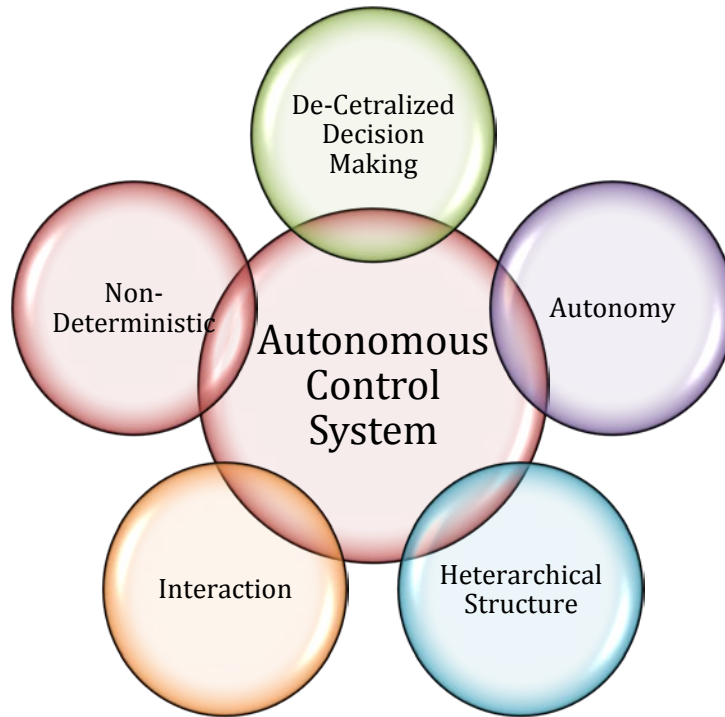


Figure 14: Effective elements in configuring autonomous control systems, according to [13].

2.3.3 Autonomous Logistic System

According to Duffie *et al.* [109], even though it is favorable to control SC globally, but it is hardly possible to provide all required information for a central planning and control system properly. In particular, when the system is complex in terms of wide scale and scope, like logistics, then central planning gets into trouble. However, it can be argued that autonomous systems have been raised versus integrated and central systems. In this paper, the authors argue that decentralized coordination across logistic processes—implemented by autonomous entities (logistics objects) — is an alternative to the complexity problem. They reflect the issue of heterarchical control structure and cooperative decision making for decentralized systems. Despite talking about the necessity of cooperation and communication between decentralized entities, they express the challenging issues in defining the degree of autonomy for autonomous logistics systems. Moreover, in logistics, autonomous systems simultaneously inherit the characteristics of distributed and decentralized systems. In other words, autonomous systems encompass decentralized and distributed systems.

Scholz-Reiter *et al.* in [110] discuss about the current and prospective situation in logistics and refer to the fact of increasing dynamics and complexity in inbound and outbound logistics. They underline the complexity in logistics in terms of the distributed value chain and then challenge the supply of relevant information for a central decision making and coordination system. Accordingly, they propose the configuration of autonomous control system through autonomous logistic processes as well as logistic objects. In that work, a list of demands and conditions for implementing autonomous logistic processes is properly given, which defines several aspects of autonomy in logistics. Some of their relevant information about autonomy in logistics is given in Table 2.

Table 2: Demands of autonomous processes in different system levels, adopted from [110].

| Logistics System Task Layers | New Demands on Logistics Processes |
|---|--|
| Decision System Organization and Management | <u>Organizational demands</u> <ul style="list-style-type: none"> • Definition of autonomous logistics processes • Limits of conventional and autonomous control • Adequate information availability • Design of strategic and dynamic distributed targets • Methods for assuring quality of distributed processes |
| Information System Informatics Methods and ICT | <u>Technological demands</u> <ul style="list-style-type: none"> • Ability of items to communicate and cooperate • Distributed data management and handling • Mobile communication technology and hardware • Localization ability • <i>Organizing software (ERP and APS)</i> |
| Execution System Material Flow and Logistics | <u>Process-related demands</u> <ul style="list-style-type: none"> • <i>Development of autonomous decision algorithms</i> • <i>Development of strategies to use immanent intelligence</i> • Ability to model autonomous logistics processes • Robustness (e.g., for objects) • <i>Divisibility of orders/mergence of intelligent objects (e.g., assembly line)</i> • <i>Local and physical reactivity</i> |

Windt *et al.* in [37] underscore the shift of capabilities from a total (universal) system to its elements, in order to describe autonomous systems from system theory point of view. In that work, according to the context of Collaborative Research Center (CRC) 637 “Autonomous Cooperating Logistic Processes—A Paradigm Shift and its Limitations” an autonomous control system is described as a collection of decentralized decision-making processes within a heterarchical structure. Accordingly, the elements inside the system, with the capability of independently making decisions, interact with each other in a non-deterministic environment. Moreover, the objective of autonomous control systems is generically explained as robustness achievement as well as superiority for the entire system through distributed and flexible handling of dynamics and complexities. However, in the work defining the autonomy level in logistics is taken as a challenging issue. They claim that overuse of autonomy (more than being tolerable) leads to abortion in achieving the goals. Additionally, they justify the application of the autonomous control system in logistics by relying on the state of the art in technology. They argue that “logistics objects are able to render decisions by themselves in a complex and dynamically changing environment”.

Furthermore, Windt *et al.* in [108] describe the autonomous control in logistics by some characteristics accompanied with autonomous logistics objects, i.e., an ability for the objects to process information as well as making and executing decisions independently by their own. According to Scholz-Reiter *et al.* [125], the autonomous system in logistics is dawn by autonomous control objects, to be used against dynamics and complexity due to its great flexibility, distributed handling, interacting, as well as goal-oriented and

autonomous decision-making. In order to realize the autonomous control objects they simply suggest the use of state of the art in smart tags, e.g., radio frequency identification (RFID). In addition, they talk about different alternatives for being considered as autonomous objects in logistics. The study about autonomous processes, control, and modeling them is extensively explained in that work. According to Scholz-Reiter *et al.* in [126], autonomous control in logistics could be described as: “decentralized coordination of intelligent logistic objects and the routing through a logistic system by the intelligent parts themselves”. Logistic objects may include products, machines, transportation means, etc., that take part in logistic processes. Indeed, this type of control (autonomy) seeks for decentralized decision makings by having a heterarchical control structure to bear flexibility and robustness for the entire logistic system, see Duffie *et al.* [127].

Moreover, Schuldt [128] pp 35, broadly investigates the autonomous control in logistics. He underlines the inherent characteristics of SN in terms of complexity, dynamics, and distributions. Schuldt addresses the autonomous logistics paradigm as a competent solution with local control and decentralized decision-making rather than centralized systems. The aim of autonomous logistics to delegate the decision-making task to local logistic elements is emphasized by him. In the work, the potentials of the autonomous control in logistics are discussed, e.g., augmenting physical objects with the computational ability and applying the respective technology for logistic objects like pallets and containers (using pervasive/ambient/ubiquitous computing), as well as the reduction in complexity is discussed. The discussion about the current shortcomings of the autonomy in logistics is relevant in this work; he says autonomy in logistics has to deal with inherent dynamics, complexity, and distribution, but requires a specific implementation level. According to him, available technologies are still limited in their computational domains, so the degree of granularity, at which the autonomy can be used, is challenging.

On the other hand, Scholz-Reiter *et al.* in [129] report about the autonomy for immaterial logistic objects, as autonomous processes in logistics, and try to answer the questions about modeling of such processes. They introduce the novel modeling structure, as Autonomous Logistics Engineering Methodology (ALEM), to model autonomous processes in logistics. Here, the autonomous control is traced in biology and physics as well as artificial intelligence and control theory. However, they explain the study about any autonomous control system in logistics by the structure of ALEM as: objectives, structure, abilities, processes, decision, knowledge, communication, and scenario.

Indeed, autonomy can be seen as a spectrum of authority, communication, and cooperation, which span a central system to an extreme autonomous system with fully independent autonomous entities. This fact is extensively studied by Windt *et al.* [37], see Table 3. Moreover, this spectrum of autonomy has been considered in the entire life of the current study and has affected the perspective of each chapter.

Table 3: Levels of autonomy and their characteristics, done by [37].

| System layer | Criteria | Properties | | | |
|--------------------|-----------------------------------|-----------------------------------|------------------------------------|------------------------------------|---------------------------------------|
| Decision system | Time behavior of objective system | static | mostly static | mostly dynamic | dynamic |
| | Organizational structure | hierarchical | mostly hierarchical | mostly heterarchical | heterarchical |
| | Number of alternative decisions | none | some | many | unlimited |
| | Type of decision making | static | rule-based | | learning |
| | Location of decision making | system layer | subsystem layer | | system-element layer |
| | System behavior | elements and system deterministic | elements non-/system deterministic | system non-/elements deterministic | elements and system non-deterministic |
| Information system | Location of data storage | central | mostly central | mostly decentralized | decentralized |
| | Location of data processing | central | mostly central | mostly decentralized | decentralized |
| | Interaction ability | none | data allocation | communication | Coordination |
| Execution system | Resource flexibility | inflexible | less flexible | flexible | highly flexible |
| | Identification ability | no elements identifiable | some elements identifiable | many elements identifiable | all elements identifiable |
| | Measuring ability | none | others | self | self and others |
| | Mobility | immobile | less mobile | mobile | highly mobile |

In addition, Windt *et al.* [13] list some enablers for any autonomous cooperation and control as: self-identification and detection, execution system, communication ability (ICT), information processing, and ability to identify alternatives. Accordingly, several methodologies are introduced to implement the concept of autonomous control in logistics. Among which are the pheromone-based, queue length estimator, due date, for more information see Windt *et al.* [108] and Scholz-Reiter *et al.* [35].

In summary, in the recent decades, the autonomy has drawn the attention of scientists and philosophers in social and political disciplines as well, e.g., in the form of federal systems. However, in these fields sometimes autonomy is put equivalent as individualism, anomie, anarchy, and chaos [130] pp 7. Since logistics is a science that theoretically and practically belongs to the socio-economic organizations with human interventions, its performance's analysis can be compared with social systems. One can briefly review the performance of autonomous systems in social communities with authentic examples from the recent liberation movements in the Middle East and North Africa. By referring to some anonymous movements in the region, after a short life of them, their performance (success) with decentralized decision-making and autonomous control for active individuals to achieve the common goal as political freedom is revealed to us. Some successes and some frustrations show the dependency of autonomy on the circumstances,

which is active in. Apparently, in those countries with more violation as well as restrictions on communications (e.g., the internet) between autonomous individuals, the goal is not achieved yet, although the individuals may be still invisibly active. On the other hand, when the pressure for restricting connections between autonomous individuals was not intensive enough then the success in movements has been quicker attained. In fact, autonomous individuals can coordinate their decisions via communication and move toward a common action. Although it is true that independency for individuals reduces the threats for them to be traced and increases flexibility of them to face dynamics, but, on the other side, they may lose their coordination in activities and lead into anarchy. Moreover, this fact of the autonomy in social systems is taken into account throughout the current work. Thus, it is tried to define a level of autonomy for logistics parties in the operational level, while the common activities and plans in tactical and strategic level is recommended to be accomplished centrally and in an integrated manner. For this purpose, it is recommended to employ the conventional mathematical programming for SCM to plan tactical processes and operations. This has to be happened by means of embedding some tolerances (freedoms) in parameters of the models and calculated them by uncertain (fuzzy) constraints. For instance, this can be done via fuzzy robust optimization modeling, which considers vague and ill-defined parameters and makes the plans with some degree of freedoms for operational level.

Furthermore, according to Windt *et al.* in [37] the autonomous controlled logistics systems can be addressed by autonomous logistic objects, which are able to process information, and render decisions with executing them by their own. In this regard, the autonomous logistics objects as Lpallets are introduced in the current work to control real-time operations.

2.3.4 Autonomous Logistic Objects

In compliance with the development of autonomous logistic processes—in SN as well as shop-floor levels—the introduction of autonomous logistic objects has been seen as essential, see Scholz-Reiter *et al.* [110] and Windt *et al.* [13]. As mentioned before, the autonomy in logistics has two generic aspects as: *autonomous processes* (immaterial) and *autonomous objects*. Accordingly, during the recent decade several concepts have been presented with the purpose of promoting autonomous objects in logistics. The procedure of developing autonomous logistic objects has intensively been amplified by the state of the art in the *internet of things*. According to Pfister [131] pp 29, “the internet of things is a global network of computers, sensors, and actuators connected through internet protocols”. This definition is more elaborated by Ukermann *et al.* in [132]. They define several aspects for the research over internet of things, as shown in Figure 15. Indeed, these features have to be followed in the research on the autonomous logistic objects as well.

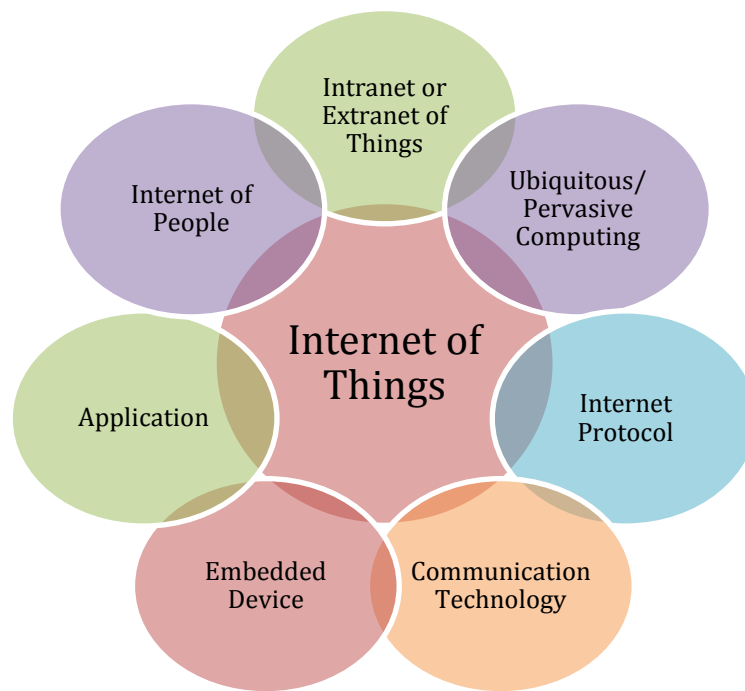


Figure 15: Cooperation of several research fields with the internet of things, see [132].

The coincidence between the ambitions of realizing autonomous objects in logistics and dissemination of the investigations in the internet of things has brought several advantages to the future research on logistics. Facilitation of pervasive communication between elements in open environments has given rise to optimistic prototypes of various intelligent and autonomous logistic objects in labs. Some authentic contributions in this field of developing autonomous objects are intelligent containers, intelligent pallets, autonomous products, and autonomous guided vehicles (AGV), for more information see CRC637 at <http://www.sfb637.uni-bremen.de/>. Thus, moving towards intelligent objects or smart objects according to Kopetz [133] pp 307, is facilitated by the concept of the internet of things, or better said, it is bred by this concept. He believes that the novelty of the internet of things is placed on "... the pervasive deployment of smart objects". Moreover, he made an illustrative review over the correlated topics and on this basis; he enumerates the drivers in this area. In his work, logistics is introduced as one primary application for the novel concept of the internet of the things. The most prominent technologies applied in these studies encompass radio frequency identification (RFID), and wireless sensor networks (WSN), which facilitate the achievement of the internet of things.

Therefore, it can be judged that the autonomous objects are the outcomes of or the building blocks of the internet of things, which have access to the universal data (cloud) for making own decisions in locals. However, competent objects in logistics must be found to gradually realize the concept of autonomous objects in practice in accordance to the internet of the things' progress. Besides, these objects must cover the prominent aspects of this paradigm as mentioned above (Figure 15).

2.3.5 Supply Chain and Production Structures

In this section, some relevant features in configuring the strategies of SC are discussed. These issues encompass the typical structures of SC and PN as well as some different handling types of material flows across them, e.g., Leagility. All the underscored subjects in this section are assumed significant to the management of the complexities' and dynamics' initiators. Moreover, the mass customization strategy is briefly explained here as an authentic target of the contemporary industries. This strategy is one of the strongest originators of complexity and fluctuations in the common logistic processes.

2.3.5.1 *Make-to-Order/Assemble-to-Order/Engineer-to-Order/Make-to-Stock*

The structure of SC and type of material flow inside them has direct effects on the emergence of dynamics and increase in complexities. Originally, material flow in SC follows a unique direction from upstream of material procurement to downstream of SC in the vicinity of customers. In this regard, distinction between the different sections (tiers) of SC, which convert raw materials into final products, is essential in differentiating the types of SC. According to the conventional SCOR model, there are five types of processes that are considered for SC as: *plan*, *source*, *make*, *deliver*, and *return*, see [134] pp 52. Between these processes source, make, and deliver, as direct related processes to physical (flow of) materials, define the three main sections existing in SC. Consequently, these three sections configure the major structures of SC in the form of *make-to-stock* (MTS), *make-to-order* (MTO), and *engineer-to-order* (ETO) [135] [136]. In addition, there are some other variants that illustrate more details about the structures of SC from manufacturing point of view, e.g., *assemble-to-order* (ATO), *buy-to-order*, *ship-to-stock* [137]. However, in general, the classification of these different types of structures in SC refers to the diffusion strength of customer orders into SC as well as to the type of manufacturing strategies. In other words, the position of decoupling point (DP) throughout the sections of SC, regarding material flow, illustrates their structures. If this point is located in the deliver section of SC then they follow MTS strategy, if it is in the make section then MTO, and if it is positioned in the source section (design of product) then ETO is the strategy of the respective SC [138] [139].

Basically, customer order DP (called order penetration point) is a physical location in each supply chain that the main stock of material — in the form of raw material, semi-finished, or finished products — is kept there [137]. This point splits up SC into two main sections as direct responding part to customer orders (order-driven) in downstream from DP, as well as the part using demand forecast for planning and production (forecast-driven), which includes the upstream of DP. Accordingly, DP is recognized as the point of concretizing the products in association with specific customer orders [135]. In addition to the physical location, as the material flow DP in SC for keeping the main stock, a similar concept is developed for information flow throughout SC, which is called information flow DP [140]. This DP in information flow defines the penetration range of customer orders into upstream of SC. Whereas up to the specific information DP in SC, planning and organizing processes consider direct orders, the upstream of that point relies on forecasts and statistical (historical) information. Conclusively, it has to be mentioned that DP and

different structures are basically influential factors to deal with alternations and dynamics in the market and, correspondingly, in logistics. Usually, the closer DP to the customer is the less spread of fluctuations occurs.

2.3.5.2 *Lean, Agility, and Leagility Concepts*

The lean manufacturing, also known as the Toyota production system (TPS), was originally presented by Ohno and Shigeo at Toyota, according to Pavnaskar *et al.* [141]. Basically, the main goal (philosophy) of the lean manufacturing is to reduce any kind of waste that does not add any value to the desired product (service) of customer. In other words, lean means doing more with less [142]. There are several conventional tools to achieve the targets of the lean manufacturing. Among them are one-piece flow, setup time reduction, cellular manufacturing, kaizen (continuous improvement), standardization, zero inventory, pull material control, etc. [141] [143]. Generally, lean concept advocates level scheduling to keep away from uncertainty, volatility, and variation. However, in some literature, it is pointed out that lean can be realized in low variant and high-volume product circumstances [144] [145], while some challenge this idea [146] [147].

On the other hand, the agile manufacturing was introduced at Lehigh University [148], in 1991. AgMS is explained as a system to be responsive in facing unpredictable and volatile markets within a highly competitive environment through a quick introduction of new products [149]. Additionally, an agile system is able to meet changes in a proper time and can profit from the changes by converting them into opportunities, as Sharifi *et al.* [150] state. Here, the outstanding characteristics of agility are considered as responsiveness, competency, flexibility, and speed, which are necessary for autonomous systems as well. Besides, the agility drivers as uncertainty, changes, and pressures are pertinent to any system confronting with dynamics. Accordingly, immediate reaction to any changes is a superior feature of agile systems, which is again a considerable characteristic of autonomous systems too. In fact, this specification of versatility spans agility concept to the autonomy paradigm with respect to higher performances [151] [152] [153].

Consequently, leanness is described as leveling schedules by means of promoting value stream and eliminating any type of waste. On the other side, agility is referred to flexibility of a system to deal with volatile markets by profiting from market knowledge and virtual corporation, to be responsive to customers [100] [154]. However, the distinction between both concepts is not unique in literature. This issue is fairly reflected in the work of Hallgren *et al.* [149], that defines three approaches about lean and agility in practice as complementary (subsequently), contradictory, and similar. See also the work of Scholten *et al.* [155] and Krishnamurthy *et al.* [156] for more details. Table 4 represents some aspects of both concepts.

Table 4: Comparing lean and agility concepts by their attributes, adopted from [149] [156] [157] [158].

| | Lean | Agile |
|------------------------------------|---|---|
| Market winner and qualifier | Cost, quality, lead time, service level | Service level, quality, cost, lead time |
| Typical product | Commodities | Fashion |

| | | |
|--|---------------------------|----------------------------------|
| Demand | Predictable | Volatile |
| Product variety | Low | High |
| JIT and total lead time reduction | Important | Important |
| Maximize profit | With less cost | With higher service level |
| Market sensitive (real demand) | Low | High |
| Virtual SC | Desirable | Important |
| Flexibility | Medium | High |
| Transparency | High | High |
| Customization | Low | High |
| Process integration | Desirable | High |
| Suitable for | Efficient mass production | Customization and responsiveness |

However, utilization of both lean and agile concepts in SC is widely discussed in literature. One outstanding strategy to make use of them simultaneously is called leagility. Indeed, in 1999, the leagile term was initially raised by Naylor, Naim, and Berry [100] to integrate the prominent manufacturing concepts as lean and agility in a unified framework used by SC. Nevertheless, the main contribution of their work to those strategies was triggered by the classification matrix in terms of flexibility, variants, and volume of products as well as the introduction of DP in SC, see Figure 16.

This approach gave rise to tasks' separation in the sections throughout SC in such a way that the lean and the agile processes become collaborative rather than mutually exclusive [139]. In this context, the agile section complies with the fluctuations in demand (regarding volume and variety) at downstream of SC by the use of MTO, whilst the lean part at upstream commits to level schedules by keeping smooth demand and MTS strategy. This takes place by pushing materials to DP, concerning the forecasted demand and the use of conventional material push flow systems, e.g., MRPI/II, which facilitate leveling in material flows. On the contrary, in downstream of DP, semi-finished products are pulled regarding the direct customer orders. This strategy decreases uncertainty in the upper side of SC, whilst increases responsiveness and flexibility in that side which directly interacts with final customers.

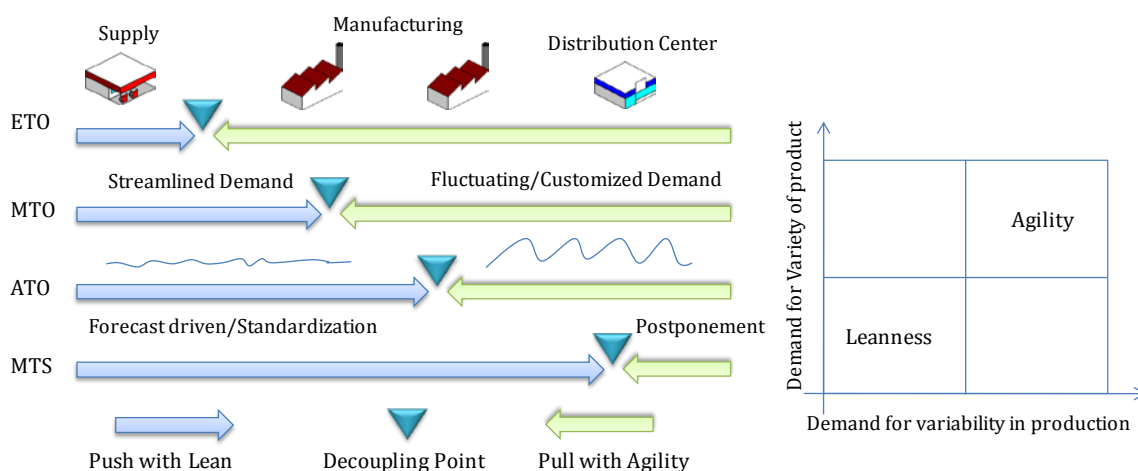


Figure 16: Leagile supply chains by lean and agile strategies using push and pull control, adopted from [100] [157] [158] [159].

Indeed, the concept of leagility resembles the two general approaches in dealing with dynamics in logistics. As mentioned before, one approach tries to reduce causes and effects of dynamics in logistics and the other one tries to employ dynamics into own behavior and become nimble. In this perspective, the lean concept represents those strategies which aim at reducing causes and effects, while agility—by employing autonomy as a prominent tool to achieve its targets—takes over the delegation of strategies with dynamic behaviors, see Scholz-Reiter and Mehraei [54]. Accordingly, the contribution of autonomy to the concept of leagility in production networks is broadly explained in the work of Scholz-Reiter and Mehraei in [48]. They developed a simulation scenario to reflect the superiority of combining of these strategies and techniques. In addition, Scholz-Reiter and Mehraei in [160] separately describe the specific correlation of autonomy with lean and agile logistics in more details. However, some results out of this work are given in the chapter about experiment scenarios.

However, in the literature, two general perspectives are given to the performance of leagile systems in terms of employing push and pull control systems. The majority of studies have been done at Cardiff and Cranfield Universities in the 2000s (e.g., Christopher *et al.* [158]). Originally, they address the push control in upstream of DP by employing the lean strategy, while pulling materials according to direct demands in the downstream of DP by undertaking the agile strategy. Nevertheless, there is a minority that talks about the competency of the agile systems with using the push flow control. For instance, in the work of Olhager [135], it is claimed that downstream of DP can employ the agile, MTO, and the push control to fulfill customized and low-volume products for customers.

Nevertheless, SC—facing dynamics and uncertainty in their demands—have already undertaken some clever strategies to overcome the challenges. Yang *et al.* [106] discuss in their literature review that uncertainty in SC can be reduced by cutting lead time and increasing flexibility as well as acceleration in responding to uncertain demand. However, between the degree of agility and the level of uncertainty a tradeoff is required, since higher agility causes more complexity. In doing so, the postponement paradigm makes a tradeoff in leagile SC dealing with fluctuations and uncertainty in demand. The main concept of postponement is about delay in concretizing the final products until the latest possible time and physical point across SC [161]. Moreover, paradigm is usually accompanied with the agility and uncertainty in manufacturing SC [155]. Based on this concept, if the level of uncertainty in demand is high, then it has to be aimed to shift DP to the vicinity of customers' side as much as possible. This directly contributes to the reduction of uncertainty caused by direct demand. In contrast, if demand is fairly smooth, then DP can be moved to the upstream of SC toward suppliers' side with the ability of using ATO and ETO strategies.

Moreover, leagility in SC properly reflects the simultaneous utilization of push and pull concepts in material flow control. Obviously, neither solely push and nor permanently pull may be appropriate when the system is dynamic with fluctuations in supply and demand. In other words, a hybrid approach to the material push and pull control aspects brings

privileges of both in a uniform context simultaneously. This issue is revealed in the Conwip and the Polca material flow control systems, preferably in inbound and shop-floor logistics. However, this can be suitably applied to outbound logistics in the scope of SN by means of leagile structures. In one of the experimented scenarios in the experiments' chapter this subject is discussed as a conceptual application of autonomous logistic objects in outbound logistics (e.g., the use of containers, cargo pallet). They are supposed to decide over push or pull systems regarding their circumstances and thereby changing the location of DP in a leagile SN [48].

2.3.5.3 Mass Customization

After transiting the mass production era in industries, gradually, the age of the mass customization has been emerged, with more respects to customers' requirements. Initially, the mass customization concept has been introduced by Davis [162] with a customizing perspective to the future of manufacturing industries. Generally, the core concept of the mass customization addresses different appetites of customers in characterizing their ideal products to design, production, and even delivery processes of SC. According to Liu *et al.* [163], the mass customization can be described as an enabling strategy for industries to produce high variants of products, regarding turbulent markets with customized demands and without any considerable compromise in quality, cost and delivery. Accordingly, Krishnamurthy *et al.* [156] describe the mass customization as a manufacturing system with customized product for a large number of customers, while keeping reasonable cost and volume and responsiveness. In fact, this significance implies the agility and flexibility in logistic operations encompassing procurement, production, and delivery processes. Moreover, the purpose of introducing the mass customization in this study is to underscore one sever strategy in industries, which can be enhanced by autonomy paradigm. Thus, pursuing this strategy reflects a feasible application for autonomous control in practice, which has to be explored more.

However, in collaboration with the concept of DP in SC, the applications of MTO, ATO, and ETO structures directly pertain to the realization of the mass customization strategy with alternative depth degrees. Indeed, spanning from standard products in MTS strategy to fully customized ones in ETO strategy, SC may undertake different policies towards reflecting the notion of the mass customization into own operations. Moreover, regarding the concepts of the lean, the agility, and the leagility in literature, the mass customization strategy can be considered as the connecting chain between these systems. This happens in such a way that a combination of these systems gives rise to meet customized orders with high responsiveness. This issue is addressed by Verdouw *et al.* [139], derived from their literature review. In addition to the required information systems, they highlight the important role of generic product model, modularity, integration platform, configuration support, and component availability to achieve the mass customization capability. Finally, the significance of flexible production processes in producing the right products and also appropriate logistics in delivering the right products to the right customer at the right time is noticeable [164] [163]. Furthermore, connectivity of the lean, the agility, and the leagile strategies through the mass customization reflects the point that SC must profit from all

existing advanced system in manufacturing and material flow to keep their competitive advantages. In the mass customization a huge attention is paid to customer orders by means of undertaking X-to-order structures in SC, (i.e., X can be engineer, make, or configure) [165]. Nevertheless, penetration of customer order into SC necessitates new approaches in fulfilling the customers. In fact, the tie between products and direct orders in the mass customization strategy manifests the notion of material pull approach in manufacturing systems. This issue initiated the leagility concept with the purpose of employing push and pull material flow controls within a unique framework.

Krishnamurthy *et al.* [156], in their broad literature review, highlight the dominance of pull systems over push in MTO approach. Additionally, they indicate the importance of decentralization in terms of authorities and decision-makings when uncertainty is the overwhelming circumstance for production. According to their work and some others, the logical connections between the outstanding terms in production systems as lean, agility, leagility, mass customization, responsiveness, decentralization, and dynamic changes, directly reflect the necessity of the autonomous control in logistics concept as well as the importance of complying with the conventional production systems/strategies.

According to Brabazon *et al.* [166] the enablers of the mass customization can be classified into four groups as: product design, process design (including SC), information systems, process management, and control approaches. Between these enablers, the modularity and the product design are irrelevant to the current study, but process design encompassing responsive SC, agility, and flexibility in logistics operations, as well as information and communication facilities are directly pertinent to the notion of the autonomy in logistics. In order to increase flexibility and adaptability of a production system to meet the requirements of the mass customization strategy, adoption of the autonomy paradigm is considered as a competent policy [167]. Operating in an atmosphere with high-variant and low-volume products, under highly dynamic circumstances have induced the employment of new strategies with privileges towards responsiveness and flexibility. For this purpose, AMS including the autonomous control and adaptive logistic processes is a competent technique [168], which is gradually evolving into practice, e.g., autonomous products, and logistic objects. Correspondingly, there are some similarities between the mass customization and the autonomous control that some of which are listed in Table 5.

Table 5: Contribution of autonomous control to environmental characteristics and enablers of mass customization

| Orientation of strategies | | |
|----------------------------------|---------------------------|---------------------------|
| | Mass customization | Autonomous control |
| Flexibility | Required | Essentially high |
| Uncertainty | High | Suitable for |
| Complexity | High | To be low |
| Individuality | High | Essentially high |

All in all, there are some crucial features which support businesses to move toward the mass customization capability. Amongst which the key enablers are: modularity,

postponement, equipment flexibility, planning and scheduling flexibility, individuality, see Figure 17. For more information see also [169] and [170] Ch. 25. Consequently, it has been concluded that the concept of Lpallets can well comply with the individuality, modularity, flexibility, and even postponement by some changes in their controllers' capability, and some adjustments according to specific requirements and circumstances. This statement can be justified by the experiments done in the experiment chapter.

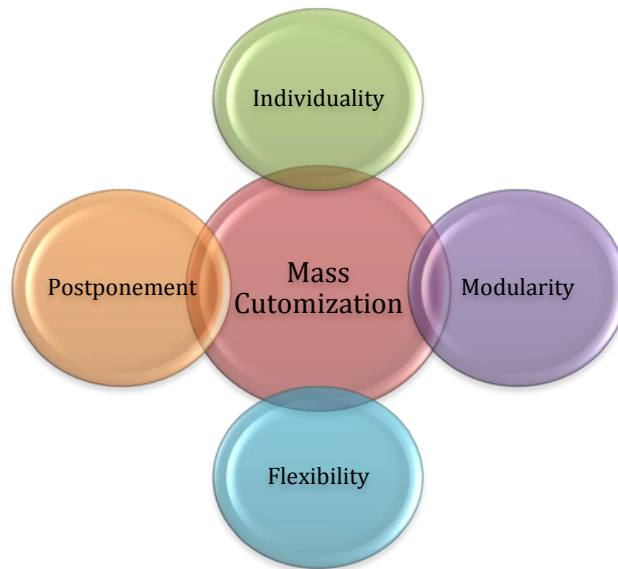


Figure 17: The practical aspects contributing in the mass customization merit.

2.3.6 Shop-Floor Scheduling

Basically, the operational level of PPC processes encompasses planning or properly saying scheduling problems with different characteristics and varieties. By drilling down through planning operations the planning horizon continuously decreases from years at the strategic level to days and hours at the operational level. Besides, information from quite aggregated state in long term planning gets updated into more detailed and on time information flow, see Figure 18. Conventionally, in operational research (OR) three generic steps are considered for organizing operations in a desired way (optimization) as planning, scheduling, and control. In this context planning usually deals with organizing operations with long term and mid-term horizons down into short-term master activities, whereas, scheduling complies with managing operations with quite short term horizon for authorizing operational activities. Scheduling is central to shop-floor operations, which are the frontier (interface) between physical operations and execution of planning and schedules.

Accordingly, the mission of monitoring and correctly handling the already scheduled activities regarding the constraints are assigned to control processes. Incidentally, outputs of planning processes are the inputs of scheduling and respectively the outputs of scheduling processes are the inputs for the control task. However, the definitions about these terms are not quite common and some alternatives have been introduced by

literature, e.g., some assumed planning and scheduling with similar missions, while some discriminate between their activities [171].

Moreover, allocation of resources to operations in an optimum way is carried out by scheduling activities, whilst selection of resources is the duty of planning with bridging design, manufacturing, and scheduling operations [172]. Then analyzing, modeling, and monitoring of operations are the task of control [171]. Nevertheless, both planning and scheduling activities are decision making processes in alternative horizons which are the core of any manufacturing and service industries [173] pp 3. Significantly, optimization of operations is central to the task of planning and scheduling.

By considering the similarities and discrepancies between these prominent terms in logistics and manufacturing, scheduling can be defined as a task with optimization objective, which “concerns with the allocation of resources to activities with the objective of optimizing some performance measures” as Bartak *et al.* [64] mention. Or as Pinedo [86] pp 1, introduces scheduling is “a decision making process that is used on a regular basis in many manufacturing and service industries. It deals with the allocation of resources to tasks over given time periods and its goal is to optimize one or more objectives”. However, in manufacturing and logistics environment resources span a wide range of physical and nonphysical objects like human, machine, runways, transporters, processing units in IT environment, etc., while activities (tasks) can cover production orders, transportation orders, loading and landing of raw or semi-finished materials, etc.

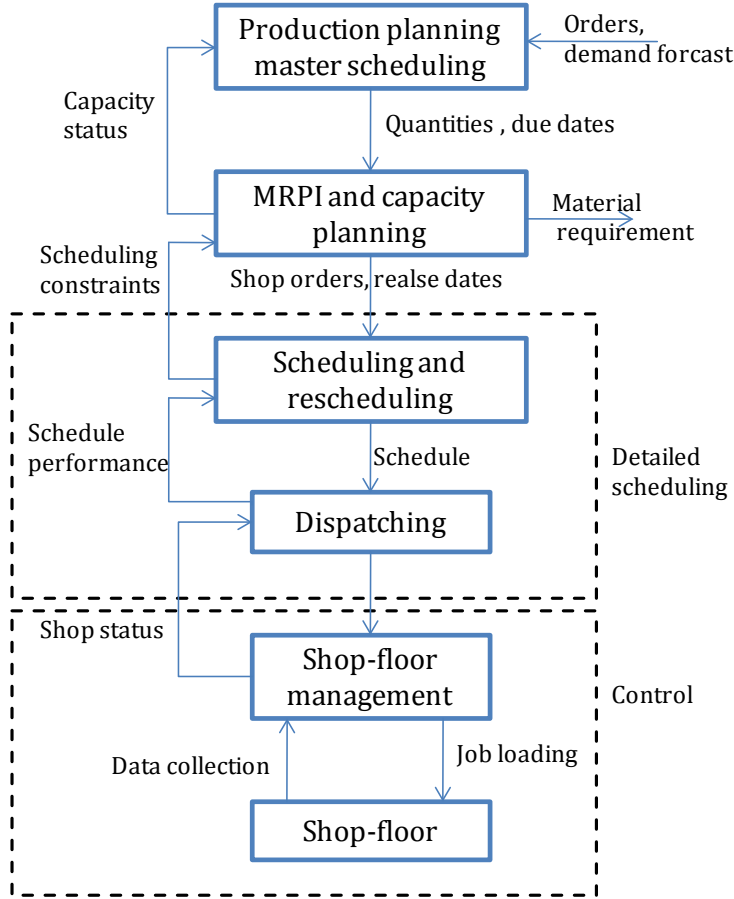


Figure 18: Information flow diagram in a manufacturing system, adapted from [173] pp 10.

However, scheduling in general encompasses three main categories in manufacturing (shop-floor) environment as flow-shop, job-shop and open-shop [174] pp 155. The major difference between these classes refers to the execution type of operations and constraints accompanied by each of the scheduling problem. Generally saying, “a scheduling problem of size $n \times m$ consists of n jobs $\{J_1, J_2, \dots, J_n\}$ to be processes on m machines $\{M_1, M_2, \dots, M_m\}$ ” [175]. Now, each type of shop-floor scheduling problem aims to allocate the jobs set to the machines’ set in the most optimum manner regarding the corresponding objective(s) [176]. In this manner, the job-shop problem addresses an ordered sequence of k_i operations $O_i = (o_{i1}, o_{i2}, \dots, o_{ik_i})$ for each J_i job that configures its technological constraint. Nevertheless, the flow-shop can be described as a special case of job-shop problem, so that every job has a similar technological constraint (processing order of O_i) like the others, distinct of being or not identical jobs. In the same manner, open-shop problem is an extension of job-shop problem, while there is no order for operating the O_i operations of job J_i on m machines, see also [177]. However, the main variants of shop-floor scheduling are briefly described in the following sections. It is noticeable that these three major classes of shop-floor scheduling problems are above single machine and parallel machines problems, which are not covered in this study, see [178] [86] pp 15.

Nevertheless, distinct from these main classes of shop-floor scheduling problems, the task of scheduling by itself, on the current and prospective manufacturing environment, is due

to more practical approaches. In other words, by increasing the rate of product individuality in assembly lines the complexity of respective scheduling problems is growing as well. Today, every single job (product) may require unique operations and treatment in manufacturing, because of non-identical specifications. So, this fact inflates the computational time of conventional scheduling algorithms and decreases the precision of offline and central solutions. Indeed, these changes (revolution) to production systems have been inducing more uncertainty and stochastic processes to practical operations in the way that the static and offline schedules are no longer so reliable. Practitioners are aware of the disability of conventional scheduling solutions within real shop-floor environments considering interruptions by breakdowns and unforeseen events [175] [179] [180]. This issue is more elaborated in the section of real-time scheduling.

However, scheduling problem is one of the most challenging problems in terms of optimum solutions, so that most of their variants are classified into *NP*-hard computational time problems, i.e., just few problem, for example, two machine problem with makespan objective can be solved polynomially [174] pp 179. Therefore, in order to solve such hard problems some efficient algorithms with near-optimal solutions are required [181]. Conventionally, scheduling problems can be solved by some global and local algorithms. Among which, some local algorithms like dispatching rules heuristics, search methods like GA, SA, tabu search, as well as exact algorithms like the branch and bound, and global heuristics like shifting bottlenecks are abundantly used in literature, see [182] [183] [184]. It is noticeable that in global algorithms still the local characteristic returns to their optimization approach with stepwise improvement through searching for local neighbors (solutions) towards the global optimum solution.

In this regard, dispatching rules are very popular heuristics, which can be used individually, in a hybrid manner with each other, or with other algorithms like GA. However, dispatching rules do the mission of local *sequence* but not the *schedule*, while other algorithms mostly do the mission of *schedule*¹. However, their combinations in the form of hybrid algorithms cover the both aspects of scheduling problems. Dispatching rules are very popular in manufacturing scheduling due to their simplicity in implementation and low time complexity [185]. There are local and global dispatching rules that look for one queue of a machine or for all machines situation, respectively. Some exemplary dispatching rules which are relevant in manufacturing environment are given below, for more information see [86] pp 373.

¹ In order to illustrate the specific point of the current work in terms of scheduling three terminologies, i.e., sequence, schedule, and scheduling policy, used in scheduling problems has to be described. Pinedo [86] pp 21, properly defines each of the them as; "A sequence usually corresponds to a permutation sequence of the n jobs or the order in which jobs are to be processes on a given machine. A schedule usually refers to an allocation of jobs within a more complicated setting of machines, allowing possibly for preemptions of jobs by other jobs that are released at a later point in time. The concept of a scheduling policy is often used in stochastic settings: a policy prescribes an appropriate action for any one of the states the system may be in. In deterministic models usually only sequences or schedules are of importance.

- *First come first served (FCFS)*, which orders the jobs in ascending manner to their entrance time. This is a local rule,
- *Earliest due date (EDD)*, which orders the jobs in ascending manner regarding their due dates; later due date less priority for operation. This is a local rule,
- *Shortest processing time (SPT)*, which orders the jobs in ascending manner according to their processing time; less processing time higher priority for operation. This is a local rule,
- *Longest processing time (LPT)*, contrary to SPT; higher processing time higher priority for operation. This is a local rule,
- *Minimum slack (MS) first*, which is a dynamic rule that sequences the job in a queue according to $\max(d_j - p_j - t, 0)$. Where d_j stands for due date of job j , p_j is the processing time for the job, and t states the current time. This is a local rule,
- *Shortest Queue (SQ) first*, which allocates new arriving jobs to the queue with less quantity. This is applicable e.g., in parallel machines problems. It is a global and dynamic rule.

In addition, initially, the branch and bound algorithm is designed to find optimal solutions for job-shop problems, though the computational time may be expensive for big problems [186]. The algorithm reduces the main problem in sub-problems by means of branching (splitting). Then by means of bounding it finds the lower and the upper bound of each sub-problem then compares them according to the objective (min/max) and discards non-improvable schedules towards the global optimum, for more information see [86] pp 179.

Moreover, shifting bottleneck heuristic like the branch and bound algorithm decreases the problem into sub-problems and stepwise combines sub-problems to achieve a schedule for the entire (global) problem. In fact, the sub-problems are several single machine problems that are scheduled independently, so that each machine undergoes a number of process steps (jobs). The jobs on a machine, in each sub-problem, have release times and due dates, achieved from the sequence of the processes on other machines. The schedule for each sub-problem reflects the sequence of all jobs on a particular machine. So, by finishing the solving of a sub-problem (a schedule) the bottleneck (critical machine) is recognized. Then, it has to be scheduled first in the next iteration. Afterwards, this bottleneck is removed from evaluations in the subsequent iterations, and then the entire process starts again for the left machines, see [187]. Indeed, the general procedure is to start with an initial condition of (first sub-problem) and then by means of stepwise improvement it finds a bottleneck (critical path in graph representation) in each step (iteration) of the algorithm. To find a better schedule in each step, the left machines to be scheduled are considered again for finding the new bottleneck machine regarding to the jobs, and then the jobs according to the evolved bottlenecks get re-sequenced on machines. This procedure causes the transition of bottleneck from machines to machines according to the machines schedule in each step, for more information see [86] pp 189.

Moreover, from another point of view, the local search algorithms can be seen as global ones, since they evaluate the global performance of alternative schedules in their iterations

and try to improve them step by step towards global optimum, regarding proceeding criteria. For instance, GA has been seen as a global search procedure too. It proceeds through local improvements, while continuously sampling the total parameter space, see [188] [189]. In other words, if the improvements of schedules in local search algorithms happen centrally by considering the interactions of single solutions on all machines (like individuals of GA in each generation), then this centralization and holistic perspective leads to a global approach. Although improvement in assignment of jobs to machines in scheduling problems happens by local search, but the ultimate performance of them is based on global assignments of all jobs to all machines. Nevertheless, if heuristic dispatching rules be applied by machines in a decentralized structure, then they must be seen as local methods. Accordingly, with dispatching rules it is not necessary to have bounded jobs, since they do not look for optimal schedule but the superiority of a rule over others at a time [180].

Furthermore, there are some common goals for shop-floor scheduling, which can be applied as single or multi-objectives. The important ones are as follows:

- Minimization of *Makespan* (total completion time of all jobs) C_{max} , where completion time of job j is equal to its completion time of final operation on the last machine C_j , and $C_{max} = \max_{j=1,\dots,k} \{C_j\}$, where k is the number of jobs,
- Minimization of *Total weighted completion time* $\sum w_j C_j$, where w_j is the importance weight for each job,
- Minimization of *Lateness* L , e.g., $\sum_k L_j$, where lateness of job j is $L_j = C_j - d_j$,
- Minimization of *Tardiness* T , e.g., $\sum_k T_j$, where tardiness of job j is $T_j = \max(C_j - d_j, 0)$,
- Maximization of *Utilization* U ,

In this manner, a scheduling problem can be generically represented by a triplet $\alpha|\beta|\delta$ format [86] pp 14. The position of α stands for the machine environment (scheduling type), e.g., F (flow-shop), J (Job-shop), O (open-shop). The state of β represents the characteristics of processing and constraints if any, e.g., s (sequence dependent setup times), $r, prmp$ represents release times for jobs and allowance of preemptions. Finally, the position of δ stands for objective(s) of scheduling, e.g., $\min C_{max}$. For instance, $F_m | p_{ij} = p_j | C_{max}$ denotes a proportionate flow-shop environment (equal processing time on all machines for job j) with m machines and the objective of minimizing the makespan. It is noticeable that makespan is sometime not the completion time of all jobs, but the time by which every machine has processed all jobs and returned to the initial situation [190].

Furthermore, in the three variants of shop-floor scheduling problems the processing of jobs may be preemptive (be interrupted by new arriving jobs with higher priority) or not that this makes the problem more sophisticated to be solved. Nonetheless, in the current work, all operations are non-preemptive. In addition, operations of jobs may have

sequence-dependent setup time which makes again the problem more complex. However, in the following, the three main classes of scheduling are more detailed explained.

2.3.6.1 Flow-Shop Scheduling Problem (FSSP)

Flow-shop is the simplest problem used in manufacturing environments like serial assembly line, automotive industry [180]. FSSP is simply a series of m machines that n jobs have to be processed on them in the same sequence, i.e., all jobs have the same route. Each job visits each machine once and after each processes on a machine the job joins the queue in the next machine in sequence. However, assignment of jobs to machines from their respective queues may follow different dispatching rules. For example, if all machines follow FIFO rule, then it is called *permutation* flow-shop, see Figure 19. In such flow-shops the sequence (permutation) of jobs does not change throughout the shop. A common problem for flow-shop is represented by $F_m||C_{max}$ which consists of m machines to minimize the makespan. This problem can be simply formulated as follows [86] pp 151.

$$\text{minimize } C_{max} = \max C_{i,j_k}; \forall i, k \quad (0.0.1)$$

s.t.

$$\left. \begin{aligned} C_{i,j_1} &= \sum_{l=1}^i p_{l,j_1}; \quad i = 1, \dots, m \\ C_{1,j_k} &= \sum_{l=1}^l p_{1,j_l}; \quad k = 1, \dots, n \\ C_{i,j_k} &= \max(C_{i-1,j_k}, C_{i,j_{k-1}}) + p_{i,j_k}; \quad i = 2, \dots, m; k = 2, \dots, n \end{aligned} \right\} \quad (0.0.2)$$

where C_{max} is the makespan, C_{i,j_k} is the completion time of job j_k on machine i , p_{i,j_k} denotes the processing time of job j_k on machine i . Additionally, it is proven that $F_m||C_{max}$ for $m > 2$ is strongly NP-hard.

Flexible flow-shop is the general variant of flow-shop problem in which instead of one machine in each step, out of c process steps, a number of identical machines in parallel exist. In this case, each job should undergo each process step with the selection of just one machine out of parallels in that step [86] pp 15.

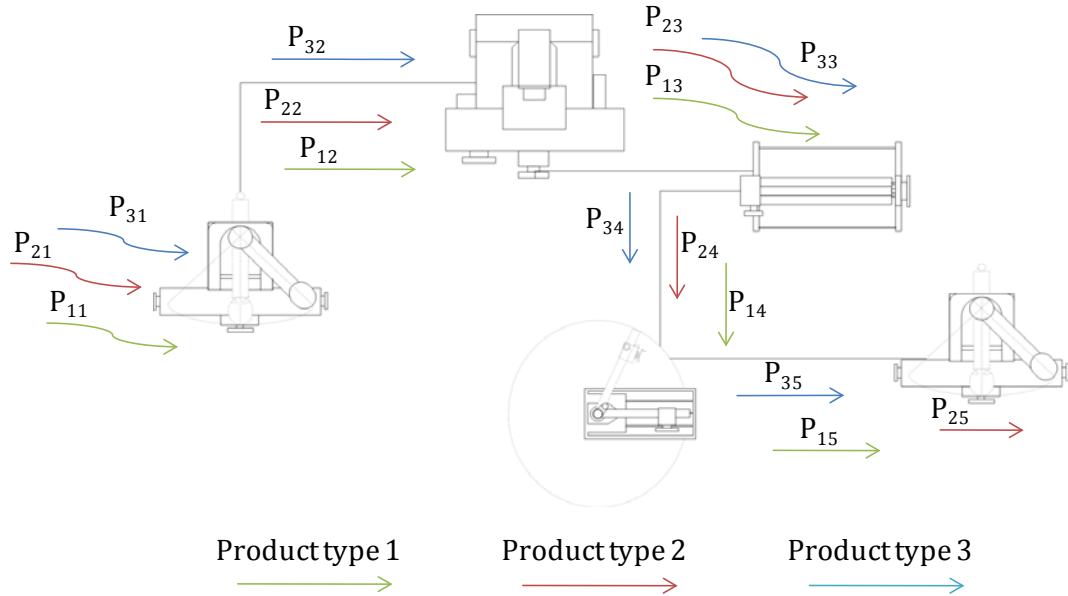


Figure 19: Exemplary flow-shop with 3 product types and 5 machines.

2.3.6.2 Job-Shop Scheduling Problem (JSSP)

The most famous and applicable scheduling problem in the assembly environment is JSSP, see Figure 20. A plenty of academic literature can be found about this specific scheduling problem with quite alternative and rich algorithms by efficient solutions, see [184]. A lot of manufacturing processes in shop-floors are pertinent to JSSP with various types, e.g., semiconductor manufacturing as a complex job-shop [187] [191]. Generally, JSSP is a well-known *NP*-hard problem for more than two machines. Basically, JSSP includes a set of n jobs to be processes on m machines, so that every J_i job must go through m machines for completion. Accordingly, each job J_i has m operations, which each of them has to be processes on one of the m machines. Once an operation starts on a machine it cannot be interrupted (non-preemptive) till the operation lasts after a specific duration. The order (sequence) of operations O_i for each job J_i is known in advance and, contrary to FSSP, it may be alternative to other jobs. Additionally, the capacity of each machine for operating jobs at each moment is one. Finally, the goal of JSSP is to find a proper permutation of all operations of jobs in such a way that the objective function of the problem gets minimized e.g., makespan $J_m || C_{max}$, tardiness, lateness [86] pp 15 and [192].

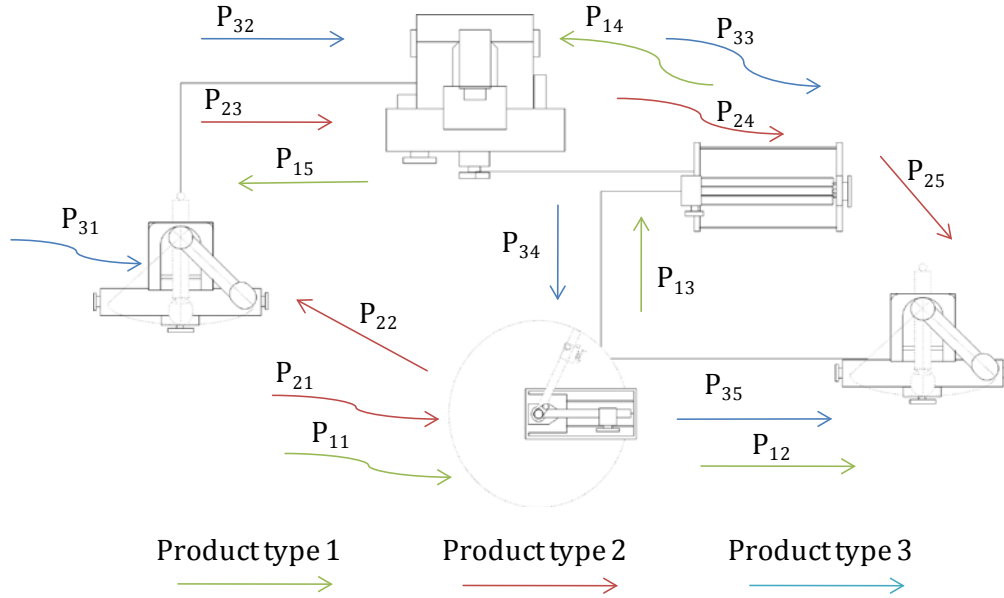


Figure 20: Exemplary shop-floor with 3 product variants and 5 working stations.

However, if a job has to visit a machine more than once this type of JSSP is called re-circulated. Moreover, flexible job-shop refers to the general problem of job-shop with identical parallel machines in each station cell instead of one machine [86] pp 15. Furthermore, some famous algorithms for solving JSSP are disjunctive programming, branch and bound, shifting bottlenecks, see [86] pp 215.

2.3.6.3 Open-Shop Scheduling Problem (OSSP)

Similarly, generic open-shop scheduling (more than 2 machines) is categorized in *NP*-hard problems without having any polynomial computation time algorithm. In OSSP, like the other two problems, a set of n jobs have to be processed by a set of m machines, so that each job has to be visited once by each machine. Whereas some processing times may be zero on some machines, each job J_i has no restriction in its processing order (sequence or route) on m machines [193]. Additionally, at most one operation of a job J_i has to be processes by a machine and only one operation of a job can be accomplished at a time. However, since the processing route of each job is arbitrary, opposite to job-shop with fixed orders, the solution space in OSSP is much larger than JSSP and FSSP, so computation time is longer as well [183]. Indeed, open route of jobs caused the name of open-shop, see Figure 21.

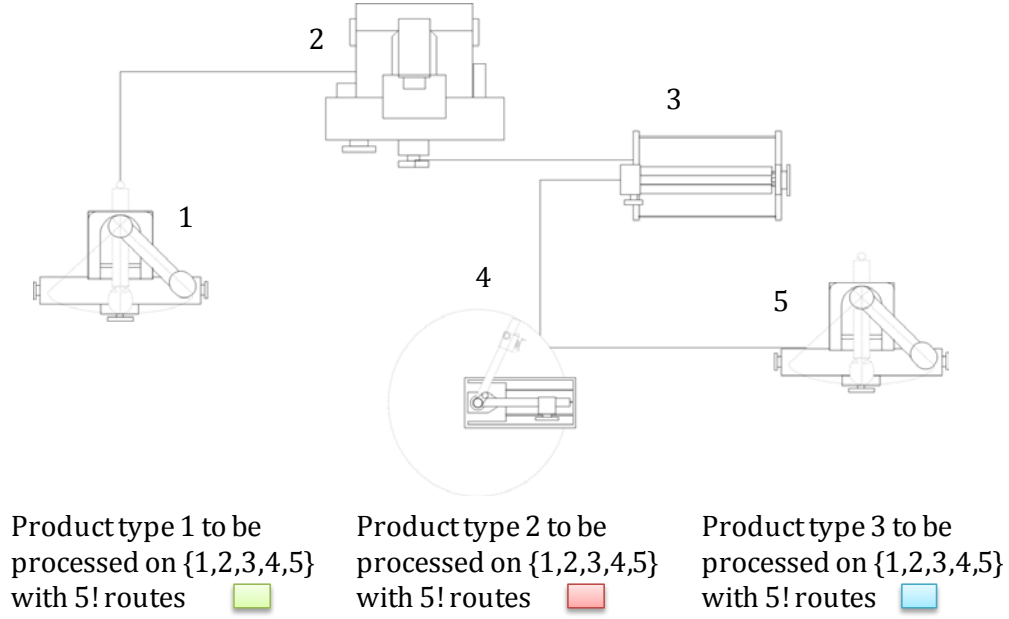


Figure 21: Exemplary open-shop problem with arbitrary selections for processing orders.

Same as other scheduling problems, there have been some researches on OSSP for years and different algorithm like meta-heuristics of swarm optimization, GA, tabu search, simulated annealing (SA), mathematical programming, etc. have been used to solve such a problem within an efficient way, as Noori-Darvish *et al.* generally reviewed them [183]. For instance, $O_m || C_{max}$ problem to minimize the makespan can be generally formulated as:

$$\text{minimize } C_{max} \geq \max_{i=1, \dots, m} (\sum_{j=1}^n p_{ij}) \quad (0.0.3)$$

where p_{ij} is the processing time of job j on machine i .

2.3.6.4 Towards Real-Time Scheduling

Indeed, uncertainty, vagueness, and stochastic processes are inherent characteristics of real-world operations, which are not taken into account by classical scheduling algorithms. Therefore, this fact has been forcing academia to look for new approaches as dynamic, online, and real-time scheduling alternatives. However, there are different understandings of these terminologies in literature also in different disciplines. Nevertheless, whereas some literature considers the three terminologies synonym or even cooperative and complementary [133] pp 239, some assume specific characteristics for them in two generic categories of offline vs. online scheduling, see work of Isović [194].

Accordingly, as Mehraei *et al.* [175] mention the online scheduling versus offline one can be explained as finding a placement and starting time for a recently arrived job within a continuously running schedule. It can be claimed that practically the number of available jobs (products) to be scheduled is not precisely known in advance. Indeed, the respective schedule progresses while the new jobs arrive or any changes happen to the system [195]. Dynamic scheduling can be seen against static one with permanent changing conditions and consideration of dynamisms in real-world. Cowling *et al.* [196] define the dynamic

scheduling as a feedback loop system by real-time information feedback into each period (day, week, month) as a loop. In this manner, real-time schedules cover both of the later scheduling approaches, whilst real-time information flow and decisions are happened in real-time within a distributed or not distributed structure [197].

In literature, a great attention has recently been paid to the transition phase from static schedules to real-time systems with the merit of simultaneously (re)scheduling and controlling on time. For instance, Lu *et al.* [198] deeply evaluate this issue by classifying real-time scheduling into static and dynamic variants. They treat such dynamic real-time systems as an open system with an unpredictable environment like e-business and internet online trading, agile manufacturing, so that neither the resource requirements nor the arrival rates are known in advance. However, they propose a feedback control in closed-loop architecture of real-time scheduling based on control theory with simultaneous schedule and control. In a relatively similar approach, the feedback scheduling was recommended by Ben Gaid *et al.* [199] as well, which works based on feedback and error control. In fact, most of the real-time scheduling studies have been focusing on scheduling of operations in electronic machines like computers and robots, whereas the focus of the current work is on scheduling in manufacturing systems.

However, obviously, a distinction between control and scheduling tasks for computing machines, like computers and robots, and scheduling and control in shop-floors must be considered. Implementation of real-time control and schedule for such machines is more straightforward in comparison with assembling physical products with human interventions in a distributed and decentralized environment. Nevertheless, the state of the art in communication and computation has brought both of the approaches closer to each other, e.g., by means of the new approach in the *internet of things* to integrate devices in a network by real-time interactions. This advance is deeply explained by Kopetz in [133]. Frantzén *et al.* [180] made a good combination between both applications through the introduction of a real-time scheduling for automotive industry. They developed a simulation-based scheduling system which is integrated with shop-floor database. It receives data from production line and sends back expert suggestions directly to operators via personal digital assistants. Application of web-based real-time scheduling and the communication means facilitates the realization of real-time systems in manufacturing environments. In addition, Savkin *et al.* [200] exploit the advantages of real-time control in electronic machines to realize real-time scheduling in flexible manufacturing networks. In other words, they employ a feedback control policy within a closed system to control (minimize) setup time as a control goal in flexible manufacturing.

Nevertheless, the issue of real-time scheduling and control in the shop-floor environment is properly addressed by Huang *et al.* [201]. They suggest the used of RFID as smart (Kanban) tags in controlling WIP in job-shop manufacturing. Application of RFID facilitates traceability of WIP and up-to-date information flow from shop-floors to ERP systems, and correspondingly provides real-time information for scheduling. They introduced this novel approach to cope with handling large variety of products (like mass customized systems).

However, their approach is still central scheduling by means of real-time information provision to ERP scheduler module. This example, illustrates the relevance of the bridge between real-time control (and scheduling) in operational level of shop-floors and higher level planning in ERP systems. In fact, it emphasizes on the importance of cooperation between real-time schedules and planning in mid-/short term levels to increase productivity of manufacturing systems in SN. It is noticeable that the approach of the current work is to keep this novelty in the shop-floor environment, while the control and schedule tasks, i.e., decision makings, happen within a distributed structure by decentralized autonomous objects (Lpallets here).

Additionally, Ham *et al.* [191] present a real-time scheduling approach for flexible job-shop problem. Besides, they give a good review on the history of real-time scheduling in manufacturing environment. They use an integer programming (IP) model to formulate their flexible job-shop problem and solve that with their real-time heuristic (RTS). However, the centralized scheduling manner like other similar approaches is common in their literature review and own work. However, by increasing the number of operations in shop-floors, realization of real-time scheduling and control task gets into trouble. In other words, intricacy of information flow, computation, and feedback control within a wide spread environment with rich distributed operations seems problematic to a central scheduler, as it is seen and stated by Kopetz [133] pp 241. On the contrary, the specific and novel approach of real-time scheduling by means of decentralized autonomous logistics objects is a fully decentralized scheduling and control system which is ad hoc.

Consequently, as mentioned previously, processes in APS— as an extension to PPC—span from SN planning— with a global perspective in macro scale— to shop-floor scheduling, with a micro scale outlook. Indeed, scheduling is one of the most important operational research processes in shop-floors regarding its definition, which is correctly met by APS. In the framework of APS the hierarchy of planning and scheduling tasks is obviously reflected, so that an optimized or near optimized operations can be achieved. Nonetheless, the move towards more realistic planning and scheduling processes force researches to come closer to real-time scheduling and control of operations through the introduction of decentralized and autonomous systems. This transition paradigm should occur in such a way that both of scheduling and control tasks in an extreme case can be merged into a real-time scheduling framework. Figure 22 simply displays a recommended information flow spanning planning information, e.g., coming from APS, to real-time shop-floor scheduling and control. Here, the contribution of autonomous controlled logistics objects in the frontier of shop-floors scheduling and control processes is symbolically represented.

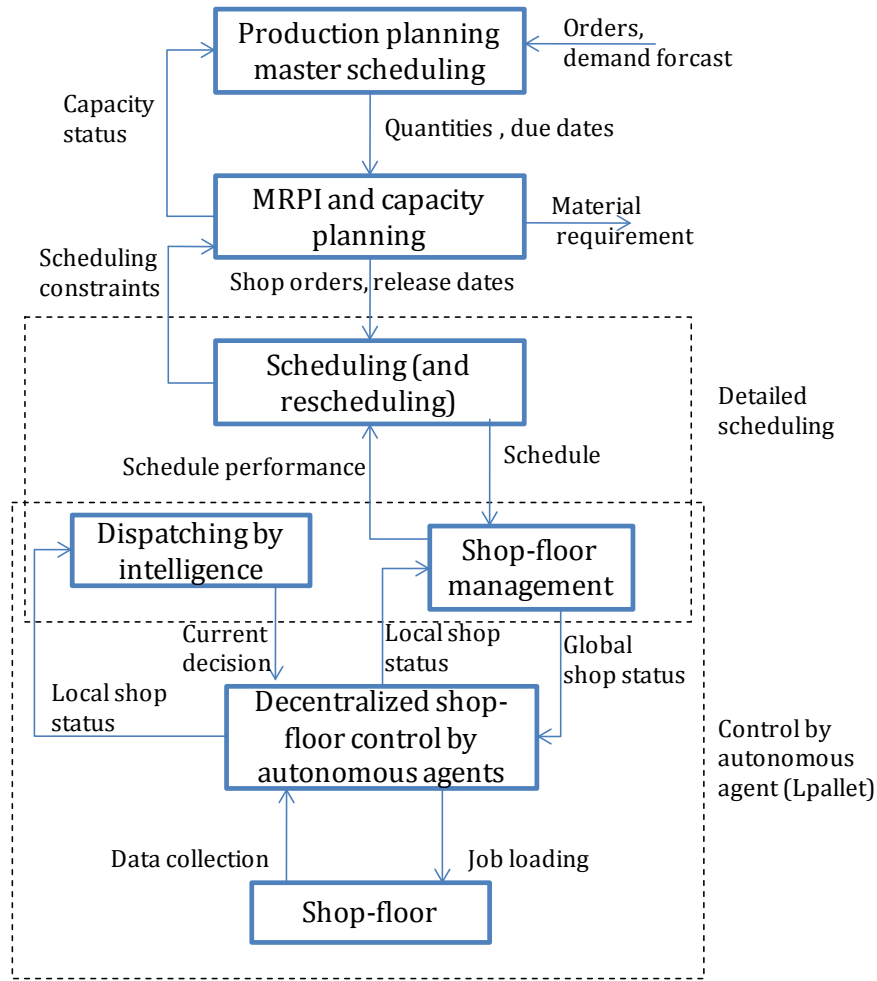


Figure 22: Information flow from master planning to shop-floor control with decentralized autonomous objects.

In other words, moving towards real-time information flow is the ultimate purpose of scheduling in the present production/logistics systems. In doing so, regarding the information flow in Figure 22, parts of the detailed scheduling and control sections can be done autonomously by decentralized objects, compare with Figure 18. Indeed, in real-time scheduling the boundary between scheduling and control is not very strict. By means of real-time sequencing and decentralized control autonomous objects do the mission of scheduling, whilst they may be connected to the higher level of information in central scheduling.

2.3.6.5 Contribution of Autonomous Control in Lpallets to Shop-Floor Scheduling

The main contribution of Lpallets to the scheduling returns to their real-time decision making ability and control, which can comply with the mission of the sequencing (routing) and the self-organized control, even without any direct communication with other players in scheduling. However, the purpose of this study is not to comply with the problems in scheduling and their variants in detail, but the main goal is to define the applicability of Lpallets in realizing the real-time scheduling and control targets. The use of Lpallets on the frontier of operations within shop-floors gives rise to distributed and decentralized control of material flow as well as real-time decision makings according to the experienced constraints and behaviors of the system.

3 Conventional Compatible Techniques (Research Approach)

3.1 Closed and Open System Review Towards Learning

Generally, systems are classified into two main groups as open systems and closed (-loop) systems. The characteristics of a system, the condition of internal operations, and the interactions of the system with the outbound environment, define the taxonomy of a system. There are several perspectives for explaining the characteristics of open and closed systems, see Figure 23. Control theory with the mathematical approach, thermodynamic with physical approach, and organizational theory with the social and economical approach outline the two classes of systems with their own points of view. However, distinct from their discrepancies in defining the specifications, some common attributes of the two classes are given in the following.

From control theory perspective, open (feedback-free) systems are those which their outputs— apart from the contents— have no effect on their performances or on the later outputs. Nevertheless, to complement the characteristics of open systems yet some aspects are due. Despite the fact that open systems depict their own boundaries with the environment (exogenous factors), the internal elements of open systems have interactions with the environment and are affected by those factors. A good example of open systems is biological or alive organisms. In contrast, closed (feedback) systems accept no influence from outside of the systems' boundaries and at the same time internal (endogenous) factors affect each other, e.g., mechanical machines. In fact, in closed systems the internal effects as well as the influences of outputs on inputs are interpreted as feedbacks in control theory. For more information about closed and open systems in control theory see e.g., Müller *et al.* [395].

As mentioned before, distinction between systems' taxonomy is dependent on the perspective of the classifier. One fundamental viewpoint in systems' classification refers to processes of systems. If the processes of a system are self-regulated then this system is recognized as closed-loop system. On the other hand, if the output of a system is not connected to the input of that, this system has no self-regulation property and is sorted as open-loop system [396] pp 80.

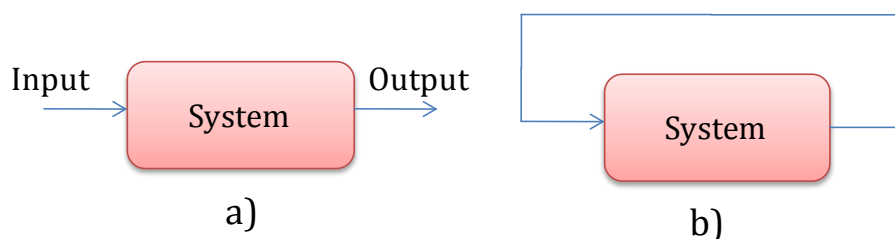


Figure 23: a) Open system with input from and output to environment, b) closed system.

Another perspective to this taxonomy is based on knowledge management perspective. In this context, system has some different definitions to physical or technical systems. Among all, one definition explains system as “A group of interacting, interrelated, and interdependent components that form a complex and unified whole” [397] pp 6. In this regard, from system thinking point of view an open system can exchange information,

material, or energy with its exogenous factors, besides its outcomes have causal relations with surrounding environment (to affect and be affected by). On the contrary, closed systems are assumed quite independent or isolated from any exogenous influences. Nonetheless, in this definition a closed system may accept inputs or send outputs to the environment, but the process of transferring inputs to outputs gets no influence from the environment [398] pp 84.

However, the big difference between the definitions for closed and open systems in social perspectives and control theory is the internal feedback factor. Whereas social and organizational knowledge stress on the isolation spec of closed systems, control theory and physics underscore the internal feedbacks and deterministic behavior of such systems. Thus, the advantage of closed systems in getting easier controlled is compensated by the drawback of being isolated from constructive interactions with the environment. Nonetheless, this discrepancy returns to the treatment of social knowledge with organizations as living mechanisms. This is necessary to note that today the organizational systems or, generally, any kind of systems that has intervention with human are considered as living systems. Furthermore, in organizational theory, the specifications of closed systems like independency from the environment, being autonomous, and having straightforward management procedure, are mentioned as privileges of this class of systems [72] pp 14. In this respect, mostly when a system is more complex than getting simply analyzed/handled it can be assimilated into a closed system for the sake of simplicity in its control rules. However, it is noticeable that not all systems suit closed system characteristics and cannot be converted into such systems.

On the other hand, in social and organizational knowledge, open systems can be extremely complex to get analyzed and managed. Accordingly, for open systems, several additional situations are assumed to be encountered with, e.g., observing exogenous changes, as well as controlling and coordinating internal processes with the environmental disruptions and uncertainty. These interactions with the environment are necessary for surviving open systems. In fact, open systems are known by their interactions with the exogenous environment. Moreover, it should be taken into account that no pure closed system in social and economic organizations can exist. There are some other arguments in literature that go beyond the issue of equilibrium dynamics and entropy (degree of disorder) in physical closed systems, for entropy see [399] [400]. They pose the discussion of assuming open systems' characteristics for biological and organizational systems. Indeed, it has been seen that such systems have the capability to maintain regulated steady states, in spite of non-equilibrium circumstances [401] pp 32. Decoding of this fact has led to development of system thinking in understanding dynamics and complex behaviors inside systems.

Moreover, in literature occasionally closed systems and closed-loop systems are assumed similar, while some papers underscore the fact that they may be different in structure. For instance, the book, edited by Cacciabue [402], gives a comparison between open-loop – closed system versus closed-loop – open system. Here, the first one accepts stimulus from the environment and a delivers response to the environment within a closed system,

having no intervention in its transformation process. The other one depicts a system that has feedback loops from output to the input together with stimulus. However, in this study closed systems are equal to closed-loop systems, similar to the second example in [402].

However, regarding the given alternative definitions about closed and open systems, logistics and production activities in a system actually resemble open systems. Indeed, intervention of human in such activities makes these systems like living organisms. Logically, in these systems the heterogeneous interests of abundant autonomous players should lead to unpredictable behaviors with huge anarchy. Indeed, nonlinearity in such open systems' behaviors and complexity in analyzing them give rise to chaotic characteristics.

Nevertheless, chaos theory applies to systems with non-linear dynamic behaviors. It is presented to introduce new tools and point of views to study complex systems, e.g., biological, weather, economic and organizational, as well as solar systems. According to Daft [72] pp 27, "chaos theory: suggest that relationships in complex, adaptive systems—including organizations—are nonlinear and made up of numerous interconnections and divergent choices that create unintended effects and render the universe unpredictable. The world is full of uncertainty, characterized by surprises, rapid changes, and confusions. Managers cannot measure, predict, or control the unfolding drama inside the organization in traditional ways. However, chaos theory also recognizes that this randomness and disorder occur within certain larger patterns of order. The idea of chaos theory suggests that organizations should be viewed more as natural systems than as well-oiled, predictable machines". However, in order to deal with the enormous complexity in such holistic systems (logistics here) with chaotic expression; according to Daft [72] pp 28 "many organizations are shifting from strict vertical hierarchies to flexible, decentralized structures that emphasize horizontal collaboration, widespread information sharing, and adaptability", e.g., US Army. This pertinent issue is widely explained in the sections about autonomy in logistics and autonomous control.

Moreover, in the book, it is competently addressed that learning for such new structured organizations is a key driver of success facing turbulent environments. It is emphasized that "the Learning organization promotes communication and collaboration so that everyone is engaged in identifying and solving problems, enabling the organization to continuously experiment, improve, and increase its capability. The learning organization is based on equality, open information, little hierarchy, and a culture that encourages adaptability and participation, enabling ideas to bubble up from anywhere that can help the organization seize opportunities and handle crises. In a learning organization, the essential value is problem solving, as opposed to the traditional organization designed for efficient performance". Although the organizational level from macro scale point of view was addressed here, but it is applicable in micro scale as well.

In summary, closed and open systems either have their own specifications that make them more difficult or simpler to get analyzed. The main characteristics of closed systems are:

iterative actions, independency from environment, ease of patterns recognition, and internal feedback loops. On the other side, the main specifications of open systems are: complexity in configuring their interactions with the environment, adaptability with the changes from exogenous factors, evolutionary persistence, performance under dynamic conditions, and analysis of internal performances (inputs, transformation, and outputs) for scanning external changes. In this regard and together with the belief that no pure closed system in living organizations exists, several systems can be imagined with the characteristics of both open and closed systems. Although any system, exposed to environmental dynamics, locates in the series of open systems, but, in between, there might be particular systems with some privileges of closed systems. Contrary to open systems with complex interaction with environment, closed-loop systems have the advantage of learning the behaviors of the systems with moderated dynamics and complexity [403].

In other words, systems with iterative processes have the opportunity to identify and recognize the patterns of those processes with guaranteeing stability and error convergence [404] [405] [406]. Consequently, this recognition gives rise to perceptions in influences of evolved feedback loops resulted from those patterns. This resembles learning mechanism in human's brain. Indeed, closed-loops cause recursive operations in which the results out of one iteration are fed back through a loop for further perception and elaboration [407]. In doing so, through the learning phase the patterns in the behaviors of a system are gradually recognized, by means of perceiving the effective feedback loops. This is exactly what machine learning methodologies, e.g., fuzzy systems, neural networks, do. Accordingly, they try to identify the feedback dependencies between effective factors by measuring the outputs against crucial factors, i.e., as inputs again to the learning process.

However, identification of dependencies may be ambiguous to the controller of a system. The more observation of effective feedback loops the better recognition in patterns brings and, thus, the better learning occurs. In this manner, analysis of closed-loop systems declines the degree of complexity in open systems and, to some extent, avoids the systems' operations leading into chaotic behaviors. This issue is explained later in the chapters of AI as well as closed-loop production systems.

3.2 Closed-Loop System vs. Complexity in SC Review

Despite the fact that no real closed system exists in organizational mechanisms with human intervention, production and SC systems are not exceptions in between. However, the existence of closed-loop systems with feedback specifications can be advantageous to control the systems. Therefore, in the current study, closed (-loop) systems are interpreted as those systems with iterative operations and deterministic feedbacks with dynamic effects. Furthermore, literature in production systems and SN studies have already concerned with the subject of closed-loop systems, although with different perspectives.

Literature review gives a broad scope of studies done in the field of closed-loop systems and reflects their advantages in the field of manufacturing, as an organizational research. Amongst several editions in this subject, there are several exploitations of closed-loop concept in manufacturing industries. Accordingly, the major ones encompass closed-loop capacity control [202], pull material flow control systems [203], and closed-loop SC and remanufacturing [204] or reverse logistics [205], which have been deeply studied. Although all of the mentioned researches comply with the closed-loop issue in production systems and indicate the same feature as closed-loop systems offer, but the mean of closed-loop in each branch differs. For example, in reverse logistics and remanufacturing the attribute of closed-loop gives rise to the recovery/remanufacturing occasion. Here, materials in their life-cycles may repeat several times the manufacturing processes. Accordingly, what is fed back in these closed-loop systems is the physical material for procurement, production, and utilization [206]. For instance, Shi et al. [207] examine a closed-loop supply chain with several perspectives. Nonetheless, their approach to closed-loop systems includes a broad scale. They analyzed the production planning problem of a closed-loop supply chain by uncertain demand and reverse logistics with multi-product. Coordination between uncertain demand and uncertain return for manufacturing is emphasized there. They employ the mathematical model to formulate their problem and to compare the results under uncertainty. Here, a good literature review on closed-loop approaches is done. Moreover, in the closed-loop capacity control the main closed-loop aspect may be the information feedback from the condition of inventory level and supply/consumption rates [33].

Nevertheless, closed-loop material flow control, as the main topic in the current study, proceeds with information feedback as well as physical cycles for control means. In other words, there may be information about the level of material flow between the two points of origin and consumption. And, at the same time, there exists a constant number of physical carrier means, which cyclically control the flow of materials in between, see the Conwip section. For instance, Helber *et al.* [203] directly address closed-loop flows in Conwip system with a constant number of pallets and expos the simplicity of formulating such systems even under a stochastic situation. In general, material pull systems with their specific flow control resemble closed-loop material flows in SC and production systems.

Furthermore, in this specific material flow control (pull), the privileges of closed-loop systems can be employed in order to moderate the complexity of flow control as well as raising learning capability for self-organization. However, complexity and uncertainty accompanied with material flow planning and control is not trivial, specially when the framework is huge. Practitioners are aware of uncertainty footprints in practical operations with human-centered problems, as stated by Sakawa *et al.* [179]. This is addressed by Gubta and Maranas [208], in particular, for logistics and production operations. In addition, Sevastijanov and R'og [209] insist on imprecise information in production systems, which is stated by literature review of Mula *et al.* [210] as well. However, uncertainty in processes, pertinent to material flows in production systems and SC, burden extra complexity in delimitating the boundaries of a specific system to be

smoothly controlled. Thus, recently, several reports have been released about complexities in planning and control of current material flows both from practitioners and theoreticians.

Bozarth *et al.* [211] present the complexities in SC and review their influences on manufacturing plants. They distinguish between two types of complexities as dynamic complexity and detail complexity across global SC members and conclude that dynamic complexities affect manufacturing operations at most. In that work, complexity is evaluated in three branches as internal manufacturing, downstream, and upstream of SC. Lin *et al.* [212] reflect an intrinsic complex case study in LCD manufacturing industry. They address highly customization and uncertainty in the field and propose special material planning called critical material planning instead of traditional MRP systems. In the paper, two examples in terms of planning and control complexity are solved with their new approach, and their better results are illustrated. Cheng *et al.* [213] comply with complexity in construction SC, adopting the supply chain operations reference (SCOR) model for their survey. Their perspective to design SC is from the strategic point of view to detailed operations. They present a java-based program to monitor processes over construction SC. In their work, complexity in manufacturing and implementation level of SCOR model is exclusively underscored.

From another point of view, Jain *et al.* [214] formulate the accompanied complexities in SC as negotiation for dynamic cooperation and coordination features, using fuzzy logic. They introduce a hybrid negotiation mechanism between agents of SC to cooperate and compete with each other. The work refers some best practices in SC under complex and dynamic circumstances to having an efficient design in their business processes. Here, the new approach to SC— as combinations of cooperative and collaborative agents— is taken into account in simplifying the huge SC complexities. Becker *et al.* [215] go to one step beyond and open the discussion of autonomous control for handling material flow control problems. They argue about resemblance of highly complex logistics networks with metabolic systems in showing complex adaptive control behaviors against dynamics. Heterogeneous goals and parameters in production as well as in products, besides, comparing these issues in metabolic, traffic, and production networks are posted by them. Ultimately, the employment of the feedback idea is posed in their work.

However, it can be seen that in all reviewed papers common terminologies in SC, as complexity and uncertainty, either in processes or demand, are underlined. This fact represents the importance of these issues in every aspect of SCM. Increase in products' diversities, short product lifecycles, mass customization, and globalization in procurement and delivery, are addressed as main reasons for enlargement in material handling intricacies.

In order to conduct a responsive control of uncertain systems, several solutions have been already undertaken. Amongst them is the exploitation of closed-loop systems by bearing feedbacks' controls. Obviously, those systems with the ability of feedback reflection are

more capable of tackling uncertainties and make suitable adaptations. Li *et al.* [216] explicitly talk about the superiority of their closed-loop model in handling uncertainty of SC. They use mathematical programming to formulate a supply chain optimization problem under dynamic and uncertain circumstances. By employing the model of predictive control and symbolizing uncertainty in their objective functions, they reflect the effect of closed-loop feedbacks in better controlling the result of the optimization problem. Actually, information feedbacks about the difference between predicted and measured inventories play a crucial role in their model.

Nagy *et al.* [217] discuss about open-loop and closed-loop control systems and compare their performances in coping with uncertainty in optimization problems. They talk about robustness of closed-loop controls by taking the uncertainty parameter into account. They also repeat online open loop operations (optimization) based on feedbacks too. Conclusively, their work implies that closed-loop systems by feedback control can considerably reduce the effect of parameter uncertainty and show more robust optimization. However, it is stated that closed-loop control with feedbacks shows some shortcomings like increasing sensitivity of other variables against uncertain variables. Nonetheless, there is always a discussion whether closed-loop feedback systems are pragmatic for current production systems or not? This is, to some extent, expressed by Kogan [218] who proposes more explorations on open-loop systems with offline control methods vs. closed-loop feedbacks. He insists on uncertainties in production yields and demand. In the paper, the performance of each alternative is expressed, besides the weakness and strength of them under different uncertainty situations are explained.

As briefly mentioned above, there are some flow control systems that inherently use closed-loops in practice. These systems facilitate the required feedbacks in controlling the entire flows. In other words, there are some approaches in production control that resemble closed-loop systems in their processes. Among all are the material pull control systems like Kanban, Conwip, and Polca. Kirshnamurthy *et al.* in [219] analyze Conwip, Kanban and Polca control strategies as closed queuing networks and express them as closed-loops in practice. In order to analyze the closed queuing network of multi stage systems in the mentioned flow strategies they propose a decomposition approach. This was done against three difficulties; as they state like "...modeling of the performance of the join stations, analyzing stations with general service times in a closed queuing network and accounting for the interaction effects of multiple classes at the various stations of the subsystem". Additionally, they offer an iterative algorithm to compute throughput (TP) and other queuing parameters for each subsystem.

Accordingly, Duenyas *et al.* in [220] address the pull production mechanism as closed queuing networks as well. They applied correlation of consecutive round trips' times as well as standard deviation of outputs' number, to approximate the performance of the network. Levantesi in his work [221] presents the practice of closed-loop systems in material flow control by introducing those pull strategies as closed-loop systems. He directly reflects the closed-loop systems to the reality, by using a constant number of

fixtures or pallets as control means. Levantesi talks about single-loop assembly system and makes contributions to multiple loop systems. And the distinction between material flow and information is taken into consideration. Moreover, he employs the decomposition technique for better understanding behaviors of the system as well as for managing them in real time. In fact, this decomposition method in the current study is interpreted as the decentralization approach in autonomy.

Gershwin *et al.* in [222] widely return to the closed-loop production systems and express the specific characteristics of closed-loop systems. They present an efficient approximate analytical decomposition method and a transformation algorithm for closed manufacturing systems under uncertainty by decomposing the systems into their building blocks for easy analyzing. Here, special attention is paid to the effect of blocking and starvation in uncertainty. In the work two, three, six, and ten machine loops are examined. Sensitivity analysis for machine parameters as well as buffer size is accomplished too. They report the suitability of their solution for closed-loop systems like Conwip, using a limited number of pallets or fixtures. As Helbert *et al.* in [223] discuss it is possible to analyze and optimize Conwip pull systems as closed-loops in production controls by using linear programming in discrete time. The optimization factors in their work encompass Conwip level and buffer size allocation to maximize the average production rate under stochastic flow lines. They exploit a combination of optimization and simulation for better modeling stochastic processes.

Ip *et al.* in [224] treat Conwip system as closed-loop and evaluate the difference between single and multi loop Conwip system with respect to service level and work in process. They solve a case study of lamp manufacturing company by means of Conwip single and multi loop control. A novel rule-based genetic algorithm is employed to find optimum parameters, e.g., cart number in loops regarding TP and demand rates. Additionally, the optimization objective, as the total cost of holding and shortage, is minimized. They conclude that the single loop has better performance than the multi one. Li *et al.* [225] address application of the closed-loop manufacturing system in semiconductor production systems and remark broader applications for that in production. In their work, a block-structured Markov chain for a two-loop closed production line is employed to improve system design and control multi loop closed systems. They develop an UL-type RG-factorization method to compute better the stationary probability vector of the Markov chain.

In conclusion, imitation of closed-loops in material flow control strategies brings the specific privilege of closed-loop systems into production systems as following. There are several advantages of closed-loop systems over open-loops reported in literature, considering different applications, see also [226] [227]. In addition to simplicity of controlling closed-loop systems, they— by having the opportunity to reinforce their experiences and getting feedback from their performances— are able to modify their perceptions to the environment (adaptation capability), as stated in [228]. The underlined advantage of closed-loops, as feedbacks, provides a better controller to modify the

dynamics of a system and enables it to stabilize the naturally unstable systems, as is emphasized by Rowley *et al.* [229] and also is shown by Gao [230]. Jansson and Hjalmarsson [231] note the usability of closed-loop systems in unstable situations for better learning the conditions. Indeed, learning is also a prominent utility of closed-loop systems. Despite some differences between intelligent and adaptive control, learning in closed-loops seems quite practical by means of feedbacks. However, as Kulvicius *et al.* [232] mention, there is less attention paid to the learning fact of those systems, which interact with the environment as agents. The state-of-the-art solution is because of their non-stationary situations and the intricate interplays between behavior and plasticity. Here, they consider the learning of global data for faster convergence and use agents for handling local data to achieve higher accuracy. All in all, as Dorigo *et al.* [233] as well as Andry *et al.* [234] refer to, learning is a mean of autonomy achievement.

3.3 Material Flow Review

3.3.1 Material Push

It is already mentioned that material planning and control strategies are basically categorized in push, pull, and hybrid strategies. Traditionally, material flow systems used to control flows by push principles. In other words, push of materials to the next processing steps as soon as its process is finished at the current step is the principle of push control. In this case, if the line or workstations are not balanced together, WIP may be collected everywhere, and overproduction can be the consequence of this system [235]. However, this control mechanism is more suitable for mass production with forecastable demand, products with unstable demands, and MTS, or similar strategies. Correspondingly, if production lines are not balanced, then push mechanism can be used by means of safety stocks and WIP in between. Nevertheless, line balancing is a challenging issue by itself when the system is instable. MRP (I/II) is the well-known method categorized into push control systems. In other words, push strategy is basically defined by MRPI/II mechanism, while demand is forecasted and then the entire planning and scheduling of production and material flows are authorized accordingly.

However, some authors partially classified drum-buffer-rope (DBR), starvation avoidance, generic Polca, and even Conwip, as push control systems as Pahl *et al.* [236], Fernandes *et al.* [237], and Germs *et al.* [238] point it out. However, it is better to classify some of these mechanisms like Conwip as pull or rather hybrid push-pull mechanisms. Furthermore, Krishnamurthy *et al.* [239] talk about three important issues in modeling push systems as “1) estimating release lead time for MRP 2) modeling future requirements for different products and 3) determining the safety lead times and/or safety stocks required to guarantee the required service level”. Usually, the service level is recognized by demand lead time and production lead time. If demand lead time is greater than production lead time, then the service level is good.

Still there are several discussions in literature that list the advantages and disadvantages of push and pull systems in confronting with different production environments. In summary,

push systems may propagate fluctuations in demand and reflect the bullwhip effect throughout SC, since the forecasted demand may meet real demand with some delays. Also, if the forecast is not proper enough, then even it can considerably deteriorate the performance of production systems [239]. On the other hand, pull systems are able to balance the lines and keep the WIP in constant level. However, it is reported that if demand fluctuates or product types vary, then pull systems get into trouble in properly performing [240]. That is why several pull mechanism are introduced by scientists to compensate the shortcomings and adapt to new industrial environments.

3.3.2 Material Pull

However, if MRP is considered as pure push material control, Kanban must be recognized as pure material pull control technique. Normally, material push operates based on the provided information about future demand either in the form of real demand, forecasted demand, or a combination of them. On the contrary, production operations in material pull are just triggered whenever the real demand takes place to meet the exact required volume. However, in between several techniques are introduced that may span the spectrum between both absolute strategies, e.g., Conwip, Polca, generic Polca. Moreover, in fact, pull system controls WIP and monitors TP, while push controls TP and observes WIP [241]. However, according to Spearman *et al.* “push and pull are not mutually exclusive approaches” [242]. Below some advantages of pull over push control can be mentioned:

- Less variance of flow time in pull compared to push; because of negative dependency in pull and distinct correlation of jobs through pull control instead of fully correlated in push,
- Less WIP and inventory, by directly monitoring them,
- Higher customer responsiveness by production stuck to direct orders.

Initially, material pull control strategy is emerged against maintaining inventory and WIP in production lines and material flow equipments. Its main idea is originally developed by “Lean/Toyota production system (TPS)” in assisting the targets, e.g., zero-inventory, one-piece flow, just-in-time (JIT) [243]. The ultimate target of pull strategy is to achieve the zero-inventory as an important goal in lean manufacturing. However, it is an idealistic goal in practice. Nevertheless, contribution of pull to the reduction of WIP and cost— by means of JIT mechanism— made a breakthrough in production systems. Thanks to this fact, reduction in flow time and increase in customer responsiveness have been achieved as well. Basically, the philosophy of JIT encourages supply of materials at the certain time of production to avoid excessive inventory [244]. Moreover, the notion of JIT gave rise to other concepts in manufacturing like as just-in-sequence (JIS), and JIT information sharing [245].

However, the potential shortcomings of pure pull systems— in properly responding to those production systems with various product types and fabrication cells— have initiated several modification studies [239]. In other words, in literature the suitability of pull strategy, conventionally, is addressed when production systems have rather high volume,

repetitive, and low variety products with relatively stable demand [100] [246] [247] [248]. Thus, any contributions to improve the performance of pull systems with the current situation of manufacturing systems, e.g., customization, flexibility, and dynamics, have been acknowledged in studies. Indeed, this fact is the strength of the current study to introduce Lpallets in pull systems with the appealed characteristics. It is noticeable that pull control regarding its approach to individual orders seems the most consistent mechanism to develop autonomous logistic objects with individuality. Additionally, a great characteristic of pull control systems is their decentralized control aspect that is mostly used in complex control environments [249] [250] [251]. This specification is one of the most underlined attributes of autonomous control concept in manufacturing and logistics environments, which is originally offered by material pull mechanism. This consistency is a strong motivation for the employment of Lpallets in pull controlled environments.

In the latter section, it was already discussed about the relevance of material pull systems to closed-loop systems in material flow control techniques. Now, according to the compatibility of pull strategies with closed-loop systems and closed queuing networks [242], it is required to concisely open the performance mechanisms of some well-known pull control systems. This is needed in order to adjust them with the purpose of the current study, as developing autonomous control in logistics and production systems as well as analyzing their performance with queuing theory.

The pull concept made a breakthrough in Toyota and later in other imitating industries for a long time. There are some prominent material pull mechanisms as Kanban, Conwip, Polca [252] pp 243, that comply with the requirements of physical closed-loop features and, thus, learning capability by means of repetitions. Additionally, there are some hybrid approaches that employ the push and pull advantages into one mechanism, e.g., Geraghty *et al.* [253] categorize Synchro-MRP in partially pull control system. However, the three aforementioned techniques are briefly explained in the following sections. Nevertheless, the purpose of this study is not to explain the types and performance mechanisms of these techniques in detail. But rather their prominent differences and the notion of closed-loop carts inside these systems are going to be underscored. In doing so, the main experiments in the current study are done in accordance with Conwip system, since it is easier to be implemented and is abundantly used in practice, e.g., semiconductor manufacturing.

3.4 Kanban

Universally, Kanban system is recognized as a pure material pull control technique that was initially invented by TPS [254] to reduce WIP in manufacturing environments. In opposition to MRPI/II, Kanban was initiated to operate based on direct customer demand. In this concept, customers are recognized as internal and external customers that each of which configures the working domain of Kanban flow. Conventionally, in this technique, materials are moved towards when demand signal (card=Kanban in Japanese) is executed by the downstream customer.

However, there are several types of Kanban that two generic of them are one-card and two-card Kanban [243]. In one-card Kanban only one move/production signal (card) is applied. When a pallet (or container) is pulled to be consumed by downstream workstation (customer) the signal of production is sent back to the upstream (supplier) to replenish the material for the respective workstation. This model is mostly used when the workstations are closed to each other. Moreover, the signals may be cards (physical or electronic) or just empty carts. Besides, there may be one buffer between both stations as outbound buffer for upstream and inbound buffer for the downstream station, see Figure 24.

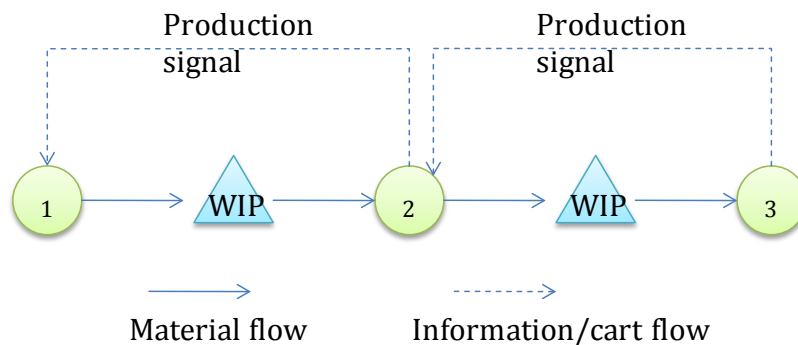


Figure 24: Single-card Kanban.

The other variant is two-card Kanban that encompasses production signal and replenishment (conveyance) signal. The advantage of this type is the separation of production execution and replenishment transfer. This means the downstream customer may ask for replenishment by conveyance signal, but this does not necessarily trigger production operations in the upstream supplier. Here, the production signal may be transferred separately, albeit the signal can be authorized in accordance to the predefined production plan or schedule, e.g., MRPI/II. This type of Kanban can specify lot-size, type of product and other data in a high mixed product environment. Usually, it is employed when the upstream workstation (supplier) and downstream customer are not close to each other and normally a supermarket (limited inventory) is placed in between, see Figure 25.

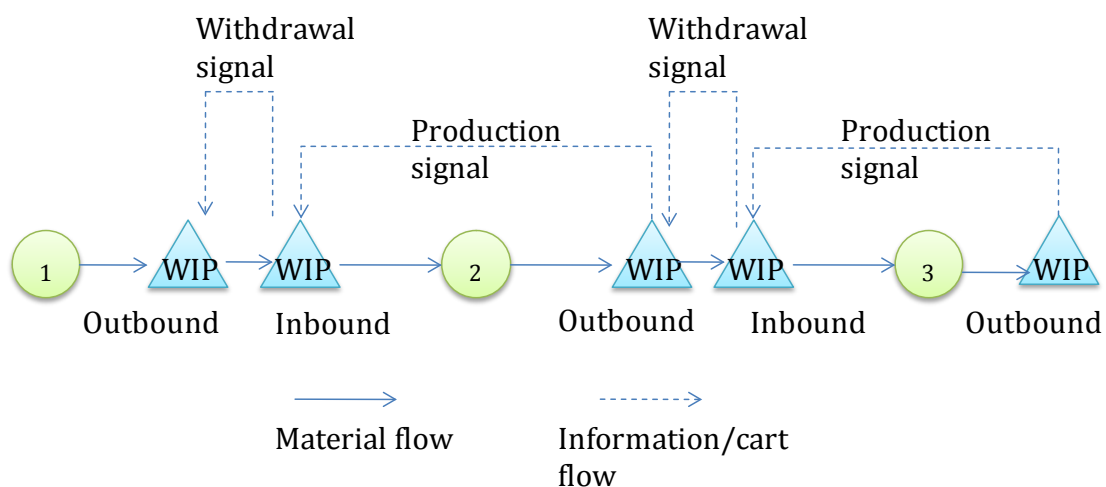


Figure 25: Dual-signal Kanban using production and withdrawal (replenishment) cards.

In addition, electronic Kanban and non-card Kanban are two variants in practice. IT may eliminate the physical cards in electronic variant that can be applied for modern automated environments and physically distant production stations. Moreover, exploitation of physical carriers like pallets, bins, fixture, etc. may represent the withdrawal and production signals by themselves and without using any card signal. Indeed, the non-card material pull systems are the specific types chosen to be used for the concept of Lpallets in this study. However, it is noticeable that Kanban is suitable for balanced lines with smooth flows of materials.

Calculation of the number of cards (Kanban) or carts in a production system to facilitate a smooth flow of material with avoiding blocking and starvation between stations is a crucial factor. Several calculation formulas and methods are already introduced to estimate the optimum number of Kanban, which represents the material quantity in process. For instance, for estimating the number of carriers in Kanban and Conwip systems from simple formulas to application of simulation, evolutionary algorithms, and neural networks, all are employed in relevant literature [224] [255] [256].

$$\text{number of cart (Kanban)} = \frac{\text{average demand lead time} + \text{safety stock (buffer stock)}}{\text{number of units per cart (Kanban size)}} \quad (1.4.1)$$

$$\text{number of cart} = \frac{\text{daily demand} \times (\text{demand lead time}) + \text{safety stock}}{\text{Kanban size} + 1} \quad (1.4.2)$$

$$\begin{aligned} \text{number of cart} = & \frac{(\text{average period demand} \times \text{replenishment time})}{\text{cart size}} + \\ & \frac{(\text{Z factor, typically 1.645 for 95\%} \times \text{demand standard deviation})}{\text{cart size}} \end{aligned} \quad (1.4.3)$$

$$\text{number of cart} = \frac{\text{replenishment lead time per Kanban} \times \text{average consumption per time period}}{\text{cart size}} \times (\text{safety factor} + 1) \quad (1.4.4)$$

$$\begin{aligned} \text{number of cart} = & \frac{\text{average daily demand in units}}{\text{cart size}} \times (\text{average daily available time} + \\ & \text{average processesing time per cart}) + \frac{\text{safety stock}}{\text{cart size}} \end{aligned} \quad (1.4.5)$$

Furthermore, Kanban system as a prominent tool in lean manufacturing shows its superiority when the production pace follows the “takt time” (1.4.6) as the pace of demand. In a leveled schedule in lean philosophy the cycle time of stations must be always under

the value of takt time. However, calculation of takt time for production lines with various types of product and unbalanced processing times is not possible. Therefore, leveling and sequencing, two important factors in the lean manufacturing pyramid, has to be implemented to achieve a practical takt time. Figure 26 defines some relevant definitions in calculating takt time, while the operations are relatively leveled under the margin of takt time.

$$Takt\ time = \frac{Total\ available\ working\ time\ per\ day\ in\ second}{Average\ daily\ customer\ demand} \quad (1.4.6)$$

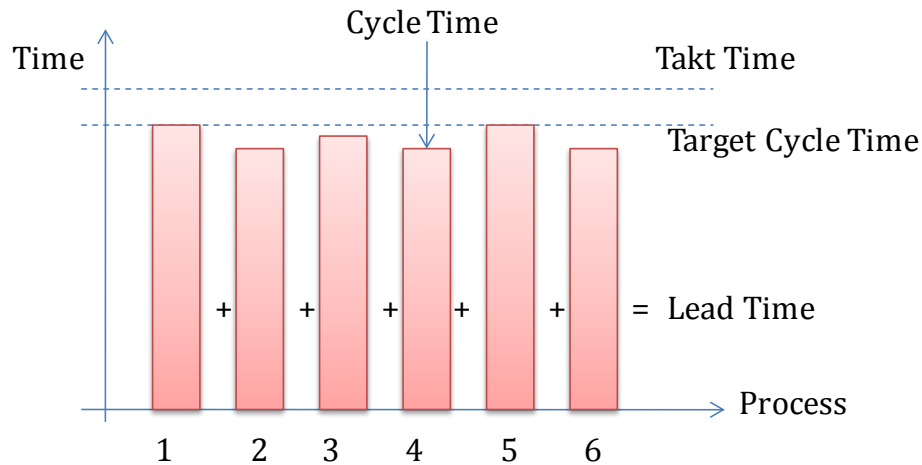


Figure 26: Definition of takt time, cycle time, and lead time of leveled processes on six machines.

3.5 Conwip

The constant work in processes (Conwip) was initially introduced by Spearman *et al.* [242] as an alternative to Kanban. It is claimed that Conwip can, to some extent, compensate the drawbacks of Kanban, e.g, Kanban is just suitable for repetitive manufacturing and unsuitable for lines with various product types as well as significant setup time. Alternatively, Conwip is sometimes called single-stage Kanban too, thus, the performance of Conwip is not separate from its predecessor. Here, the main difference is that Kanban cards (cards) control the WIP between each two stations, while in Conwip just a set of cards control the entire WIP of the Conwip line. In addition, since Conwip controls a set of stations in a production/assembly line instead of just two stations, it can be used by a larger variety of manufacturing industries.

In other words, a generalization of Kanban system is called Conwip that its repetitive trajectory spans input to output of a production line. Although it is true that Conwip is usually used for single production lines, but other variations of Conwip exist that may feed more than one line, e.g., multi Conwip system. This mechanism is usually activated by a backlog list may be filled by MPS from mid-term level planning [242]. Alternatively, a production order can be authorized to the first stage of production when the final product is consumed by its demand in the last stage [257].

The main advantage of Conwip is the constant level of WIP throughout the Conwip line that avoids overloading from capacity or keeps a specific level of congestions/inventory in the line (maybe equal to buffers capacity or bottleneck production rate). In summary, Conwip arranges a smoother flow than Kanban, and it makes use of push mechanism in its performance between release of job to production line and delivery of that in final station, see Figure 27. Additionally, as Lu *et al.* [258] claim, Conwip is suitable for facing uncertainty and dynamic environments, while implementing a pull control strategy.

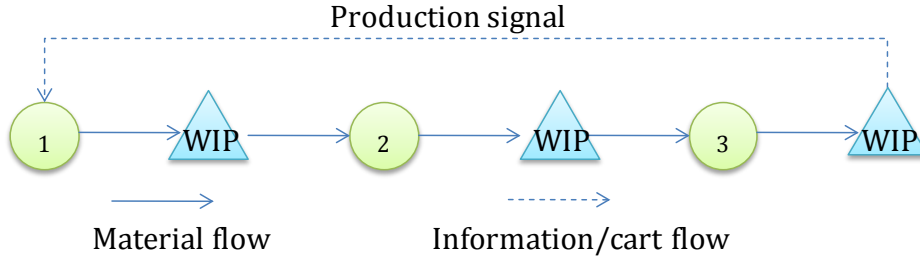


Figure 27: Simple one-line Conwip system.

In Conwip system no new release of job to the line happens before a job gets completed on the line. Thus, application of the constant number of carts for conveying materials through a production line seems a quite practical solution for implementing this mechanism. Additionally, in literature it is addressed that Conwip can easily provide lead time offset [241] by means of pushing materials between load and unload stations in a Conwip line.

However, the easiest and the mostly used equation for calculating the number of Conwip cards (carts) can be achieved by using little's law (1.5.1). Here, μ denotes the average TP of the production line, T stands for the average time for one card (cart) of product to proceed the whole line (average flow time), and x represents the low efficiency inspired by shortages in supply or machine breakdowns (can be eliminated), see Huang *et al.* [259]. In general, Little's law explains the relation between WIP, flow time and TP. Thus, dependency of these crucial factors reflects the dynamism in controlling material flows. Consequently, when at least one of the variables stays constant (e.g., WIP in pull mechanism) the dynamics of the entire system decrease.

$$Average\ flow\ time = \frac{Average\ WIP}{Average\ TP} \quad (1.5.1)$$

$$Average\ number\ of\ cards = Average\ WIP = \mu \times T \times [1 + x] \quad (1.5.2)$$

However, if the line is not leveled or any bottleneck machine exists then they have to be taken into account. For instance, in a line with a bottleneck, the cards calculation is like following, according to Huang *et al.* [259].

$$v_i = \sum_{j=1}^m v_{ij} u_i \times 24; i = 1, 2, \dots, n \quad (1.5.3)$$

$$\mu = \min v_i ; i = 1, 2, \dots, n \quad (1.5.4)$$

$$T = \sum_{j=1}^m (t_{ij} + t'_{ij}) ; i = 1, 2, \dots, n \quad (1.5.5)$$

where v_i is the average line output of job i per day, v_{ij} denotes the average output of job i per hour in machine j , u_{ij} is the utilization of machine j for job i , t_{ij} is the processing time of job i in machine j , t'_{ij} is the inventory time of job i in prior to machine j , and in order to reflect the low efficiency of machines, like breakdown and shortage in supply, a low efficiency coefficient x is introduced too. Nonetheless, the calculation formula can be adjusted according to the type of manufacturing system. For example, in semiconductor industry the calculation may vary from cold rolling industry.

All in all, in the current work, Conwip mechanism is selected to comply with the need of repetition for learning the general behavior of production systems as well as individualization. Indeed, by means of Conwip control the respective carts or pallets, which carry products throughout production lines, obtain a cyclic trajectory within the system. Thus, they can collect the required information for making further decisions via learning. This is deeply discussed in the subsequent chapters. It is noticeable that in conventional Kanban and Conwip systems the assumption is that production line is leveled in terms of operations' times and capacity of machines. However, this issue can be improved by means of flexible production lines and autonomous logistic objects to compensate the time gaps between operations and machines' capacities.

3.6 Polca

In order to meet the requirements of modern manufacturing environment, with high-variety in product's types and customized products, the Paired-Cell Overlapping Loops of Cards with Authorization (Polca) mechanism, as a quick response manufacturing (QRM) tool, is introduced by Suri [252]. QRM is a new approach in manufacturing with the target of lead time reduction in manufacturing industries. Polca spans both push and pull systems and make a hybrid mechanism absorbing the advantages of both.

Basically, production lines that produce different types of products have to be divided into subsets of production cells with similar processes of analogous parts. These cells may vary in terms of different operations, material and size of products, and, etc. Polca is quite compatible with the characteristics of job-shop manufacturing environment with various routings of products. Thus, in this case, it is superior to Kanban and Conwip. Generally, Polca cards encompass release authorization cards and production cards (something similar to the dual-signal Kanban in a wider space). In this case, release authorizations are issued across production cells according to the predefined plan and schedule, e.g., MRPI/II or MPS in higher level than operational. In other words, production follows the mid-term plan and, to some degree, the short-term prepared schedule. But the authorization of operations, dispatching, and material routings are all done by Polca in operational level distinct from push system. However, despite the release authorization time (authorizes the

beginning of a job's operations), the production operation cannot start before availability of production Polca card [240].

It is noticeable that this specific feature of Polca is favorably proposed by the current study as a practical solution to offset existing dynamics of logistics and production systems, by means of predefined plans as well as real-time operational executions. In this work, it is profoundly explained that embedding minor, but enough, freedoms in mid-/short-term plans and schedules provides the opportunity for autonomous objects to compensate the fluctuations and changes in the systems' conditions and make offsets by their own. Besides, pulling material in operational levels may decrease the effect of fluctuations by means of stabilizing the level of WIP and TP as well as using direct demand instead of uncertain forecast.

However, the Polca cards generally rotate between two cells (in round trips), see Figure 28. In particular, they stay with jobs throughout the journey over first and second cells and then after completion in the second cell they get back to the first cell gain. It is mentioned that Polca cards do not control the flows between stations inside each cell (contrary to Kanban), but preferably they control the movements between cells. Thus, the internal flows' control has, to some degree, enough freedom to perform adjusted control probably regarding the current circumstance inside cells, e.g., machine breakdowns, inventory limitation. In addition, Polca cards stay with jobs in their journey throughout two cells, which is not necessarily the case in Kanban. Nonetheless, if instead of cards, physical carts are used, then jobs and carts practically stay with each other for more than one station or cell. Moreover, some advantages of Polca, e.g., over Kanban, can be mentioned as follows.

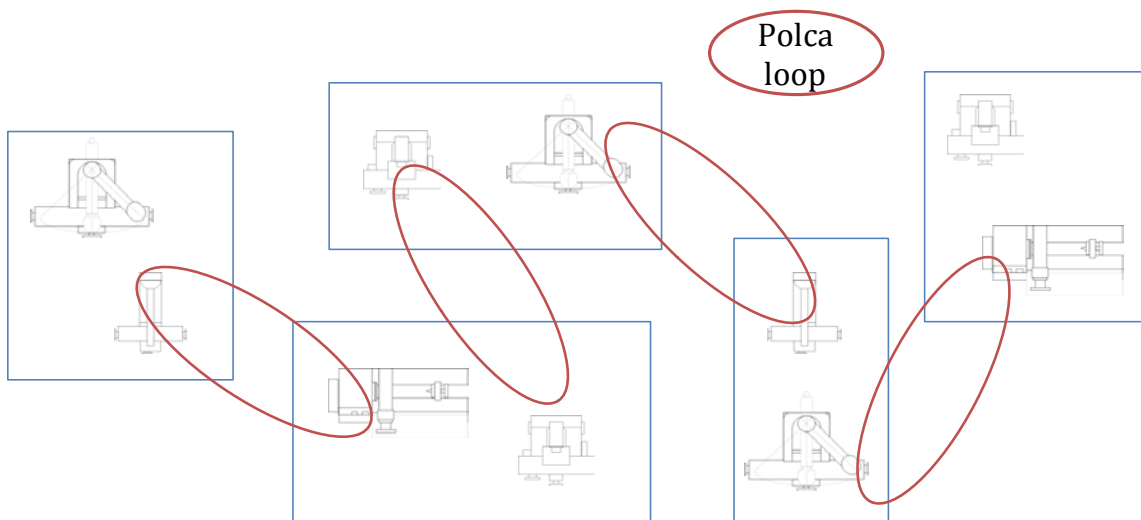


Figure 28: Polca control between production cells in an exemplary shop-floor, according to Suri [252].

When a Polca card arrives to a cell it means the downstream cell has the capacity to work on this job imminently. Otherwise, the cell is busy and processing on the job in the preceding cell increases the backlog for successive cell. This particular procedure in Polca

increases the flexibility of production cells to produce different products and delivers individual treatment for each job by use of its specific Polca card/cart. Conventionally, Polca cards do not define which job has to be started in a cell. This information is received from higher level planning and scheduling outputs, which normally are based on push results of MRPI/II. Consequently, combination of push and pull controls in this technique gives rise to moderate unexpected events by means of the existing limited freedom and decentralization in operational level. Besides, this technique leads to avoidance of chaos in material supply and delivery— due to excessive decentralization in decisions— by assistance of central push decisions (MRPI/II outputs). Therefore, available capacity and explicit demand mutually work together to execute a production operation. Since Polca is designed for environments with mixed-customized products, it can compensate the fluctuations in inventory levels and absorb the variations in demand and operations [252] pp 153, through overlapping loops in paired cells. In addition, for internal scheduling of cell exchange of information between correlated cells as a potential customer as well as a supplier is provided in Polca, which is advantageous at the presence of dynamics.

In summary, each type of pull mechanisms can suit specific industries with particular characteristics. This holds true for push systems too, with decision makings based on aggregated information. Nevertheless, in general, exploitation of pull systems inherently conveys the merit of decentralization in material flow control to shop-floors as well as SN. In literature, it is often addressed that Kanban goes well with relatively stable production environments with high-volume and low-variant products. Obviously, this system does not match the objective of the current study to deal with flexible and dynamic environments. On the other hand, there are some reports about the competency of Conwip and Polca in facing dynamics in manufacturing and logistics environments. These performances become the incentives for this study to employing pull mechanism in developing the concept of Lpallets.

Conwip with its very simple implementation procedure and Polca with its aptitude in utilizing the advantages of push and pull principles within one mechanism have inspired the concept of learning pallets in bridging the gap between the concept of autonomy in logistics and these conventional material flow control techniques. However, the technique of implementing Polca or Conwip in practice is not covered by the scope of this study. Instead, the notions of Polca, Conwip and Kanban are employed to reconfigure the current business processes in material flows against dynamics in logistics. This novel contribution provides the great circumstance for the means of material conveyance, e.g., pallets, fixtures, carts, to become autonomous by means of learning and intelligence.

4 Introduction of Learning Pallets and Applied Methods

4.1 Learning Pallets (Lpallets)

In order to achieve the measurability of the proposed framework for feasibility of autonomous logistic objects and conclude it in the current work, the specific aspect for developing autonomous objects is selected to be partly examined. In other words, after the brief revision on the current performance of SCM over entire logistics and production processes in SN, it is defined that feasibility of autonomous processes in logistics can take place at lower levels of planning and scheduling processes rather than relatively tactical as well as strategic decisions. It was already argued that integration of planning is a crucial prerequisite for coordination and efficiency over disseminated members and their operations in SN. On this basis and according to the purpose of this work as feasibility of autonomy with respect to current performances in logistics, the suitable candidate for undertaking autonomy in logistics are the operational and partially tactical decisions, regarding their localized features and influence realm.

Moreover, respecting the definition and aspects of autonomy in logistics, it is concluded that autonomous processes are supplementary and can be completed by autonomous objects in logistics. Even though autonomous processes without any physical autonomous objects may be solely developed, but it should be taken into account that logistic processes have direct interventions with physical materials and flow of them. So, this issue leads the direction of any study about autonomy in logistics to considering development of competent logistic objects in order to measure the performance of autonomous logistic processes in general.

In doing so, after a broad investigation over potential objects in logistics—spanning from single products to containers and transporters—it was concluded on the particular objects which carry materials in inbound as well as outbound logistics with flexibility regarding their various types. These novel objects are simply pallets by their variants. The selection of these specific objects is the result of several explorations in manufacturing and material flow strategies and control methods. Accordingly, the strategies and control methods have been deeply investigated in accordance to the prerequisites and fundamentals of autonomous processes in practical logistics. It has been figured out that the basis of autonomy is located on decentralized control with heterarchical structure, Intelligence for rendering real-time decisions autonomously, local operating territory, communication and interaction, see Figure 29.

So, it has been looked for those systems in logistics and manufacturing, which can comply with the whole or part of the requirements in realizing autonomy, without any major reconfiguration or configuration of new performance rules in logistics. During the investigation, it was distinguished that the decentralized and local control—contrary to the ordinary beliefs—has been employed in material flow control strategies for years. This strategy is not more than the strategy of material pull control systems developed initially by lean manufacturing philosophy. The notion of decentralized control and local information are deeply studies in literature, e.g., Liberopoulos *et al.* [260]. As it is well known, originally, lean manufacturing has commenced the exploitation of pull system to

control constant flow of materials, according to real orders, and to avoid unevenness (fluctuations) in production. However, the primitive method for pull system was Kanban that has been extended to more advanced methods like Conwip and Polca in alternative circumstances. Later, the concept of material pull control has deployed its performance area from single shop-floors to entire SN operation zone.

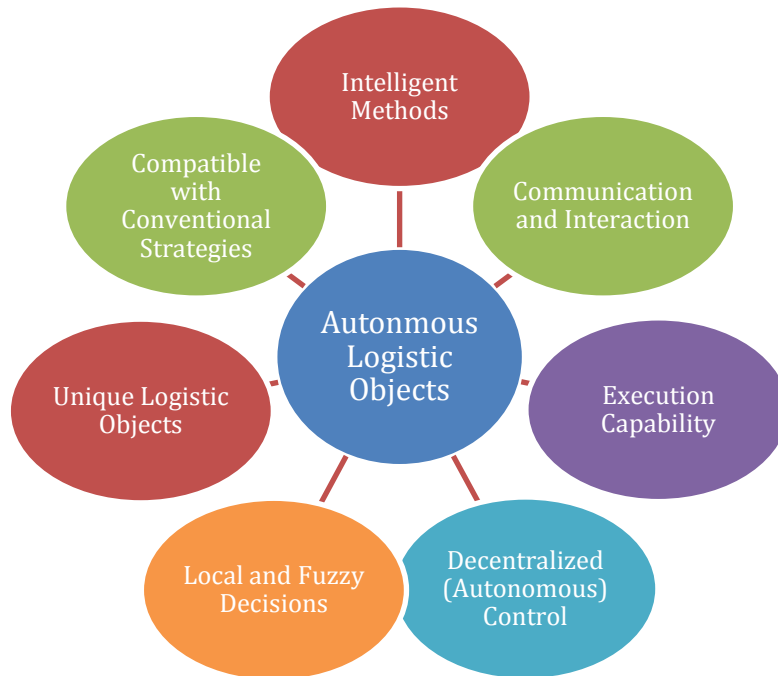


Figure 29: Features of realizing autonomous objects in logistics.

Furthermore, on the top of the pull notion and its direct relation to real orders, the manner of pull execution in practical logistics (specially shop-floors) has become relevant. In other words, application of pull cards (signals) in practice is substituted or coincidentally authorized by the circulation of conveying means (carts) in a closed loop system. This issue is reflected in the work of Zhang [261] as well as Li *et al.* [256]. This privilege, in terms of the good-natured coalition between three important aspects of autonomous logistic objects, which is taken place in such carts of pull systems, has been seen as a great opportunity for developing autonomous objects. Indeed, the four prominent features in autonomy as decentralized control, real-time operations, compatibility with conventional pull systems, and unique material flow objects, engaged in frontier of operations, are simultaneously reflected by pallets (one abundant used cart) in practice of pull systems. In this manner, the idea of making autonomous pallets has been seen as the most feasible treatment for realizing autonomy in some parts of logistics. In other words, these conventional competencies motivated the idea of autonomous pallets in practice.

In doing so, the research for autonomous objects in logistics is sharpened and delimited to a specific area of logistics, which resembles physical material flows by means of pull control or alike. Therefore, the different systems in pull control strategy have been generally reviewed. Besides, the pertinent aspects of each system to the concept of autonomous pallets are underscored in the next sections. However, after the feasibility

study in those pull systems suitable for autonomous pallets some other sections became important in developing the concept of autonomous pallets in practice. These sections had to illustrate the working area of autonomous pallets in practice as well as answering the main question about how to realize autonomous control for such autonomous objects.

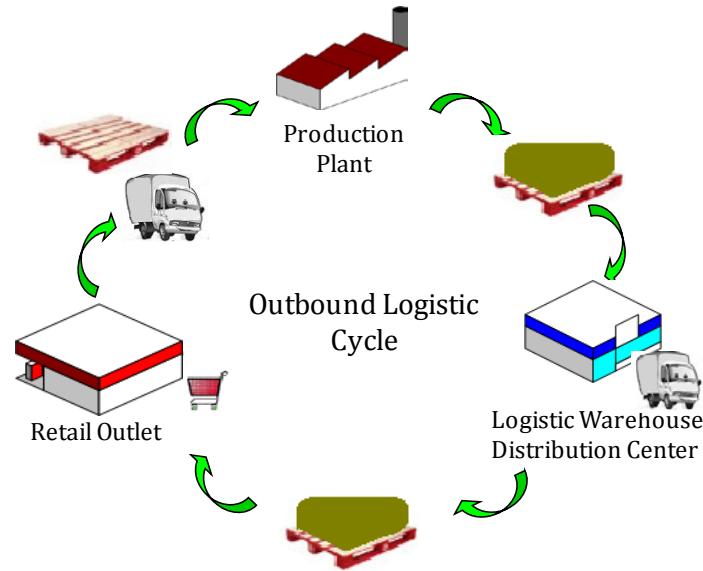


Figure 30: Exemplary outbound logistics with closed loop pallets circulation, authorized by third party logistics.

In the current work, despite the short discussion about the potentials of autonomous pallets in inbound as well as outbound logistics (see Figure 30), it has been solely focused on application of autonomous pallets in inbound logistics, i.e., shop-floors with scheduling problems. However, in addition to this performance area, proceeding with the core of autonomous control for autonomous objects is a challenging issue in developing any autonomous logistic objects. Accordingly, autonomous control with the result of independent decision making, regarding the perception of autonomous objects about their environments, cannot be realized without any intelligence. Besides, it is known that intelligence is the product of learning [262] pp 50. For this purpose, those methods built-in the intelligence, as the result of their performance and outputs, have been taken into consideration. In fact, the addressed intelligence must be reflected as intelligent controllers for autonomous objects moving through stations in logistic facilities e.g., warehouses, shop-floors, machines.

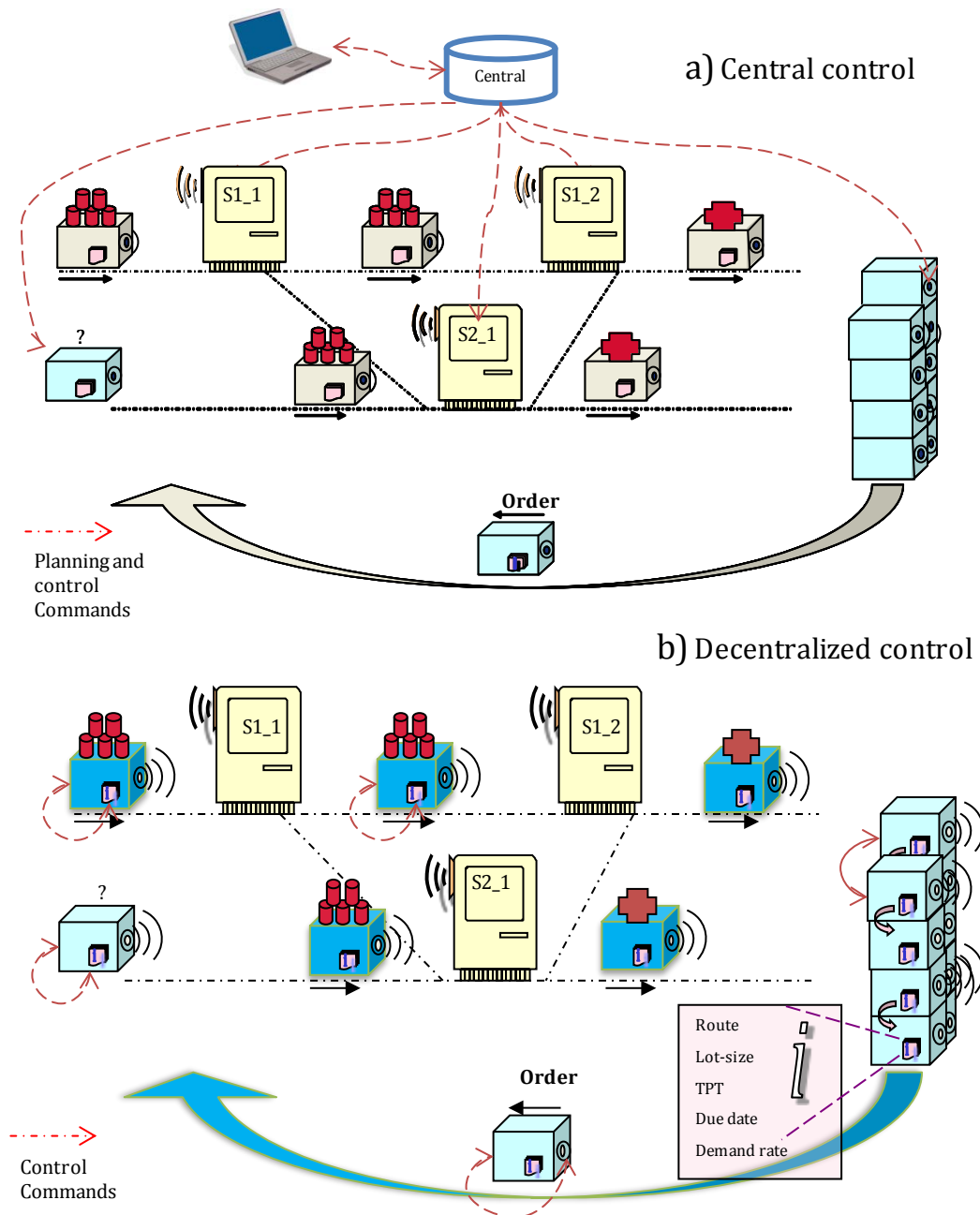


Figure 31: Exemplary a) Central control b) autonomous/learning pallets with intelligent controller, in shop-floor.

With respect to the fact that learning can be interpreted as a collection of experiments, which are rendered as knowledge for intelligence (learning by doing), the natural closed-loops in pull systems automatically facilitate the require collection of experiments (data), see Figure 31. Then the experiment must be translated into knowledge to support further decisions.

Accordingly, pallets in closed-loops after some training rounds— just following any changes happened to the system— can distinguish new conditions and adapt themselves to them. Additionally, learning can be a requirement of being autonomous. Beyond the research on intelligent products, containers, and autonomous agents (see CRC 637 Autonomous Cooperating Logistic Processes A Paradigm Shift and its Limitations,

<http://www.sfb637.uni-bremen.de>), learning ability is an alternative to provide required information for autonomously decision making [263]. It is noticeable that this alternative is not in parallel of other options, but rather is complimentary. Indeed, learning happens in closed-loop systems, which can experience new changes. It is noticeable that learning of pallets without adopting agent negotiation can reduce the technical complexity of information exchange between agents in real-time. On the other hand, it reduces the quality of proper decisions based on real-time dynamics in the system, since no exact awareness about other agents' situation is configured.

Moreover, learning for intelligent decisions approximates the concept of autonomous pallets to the notion of "*learning pallets*", as a prominent representation for autonomy and learning capability/requirements for such objects. In order to meet the competent techniques for the purpose of learning and intelligent decision making based on nondeterministic circumstances two main pillars must be considered. Artificial intelligence and Fuzzy system are the pillars to reflect both intelligence and decision making under uncertainty.

Jones [264] pp 16, generally considers some techniques for AI that among which are machine learning, evolutionary computation, and ANN. According to him, evolutionary computation techniques—encompassing evolutionary strategies like GA and SA, as well as swarm programming—imitate the behavior of biological life. Moreover, he mentions that neural networks (NN) are the standard techniques in intelligent classification and learning. Thus, the application of them is undoubtedly one pillar of intelligent decisions in autonomous objects facing complicated circumstances with various decision factors. Therefore, between the available techniques for reflecting AI in autonomous objects the famous ones are selected to be examined by Lpallets in several simulated production scenarios. More precisely, GA, SA, and a specific neural network are explored to be used by Lpallets in this work.

In addition to the mentioned intelligent techniques, fuzzy set theory and respectively fuzzy controller is recognized as another pillar of autonomous decisions. It is obvious that autonomous objects are faced with uncertain and vague situations that hinder rendering decisions based on precise information. In doing so, the best employed technique, has been presented so far, is fuzzy set theory. Indeed, fuzzy controller (system) is abundantly used in practice for any object with property of rendering fuzzy rule-based decisions. Accordingly, Lpallets, being equipped with fuzzy controller, are able to cope with inherent uncertainties in real-time decisions as well as executions. Furthermore, a coalition of fuzzy set theory with other AI techniques brings about several superiorities in the performance of intelligent objects under vagueness. Respectively, it is already known that real-life situations are accompanied with vagueness and fuzzy situations, as is emphasized by Subramaniam *et al.* [265]. However, it is noticeable that another alternative for dealing with uncertainty is the application of stochastic and probability theory. Nevertheless, in this case the probability distribution of stochastic parameters must be known in advance, which is not usually configurable in logistics with autonomous objects.

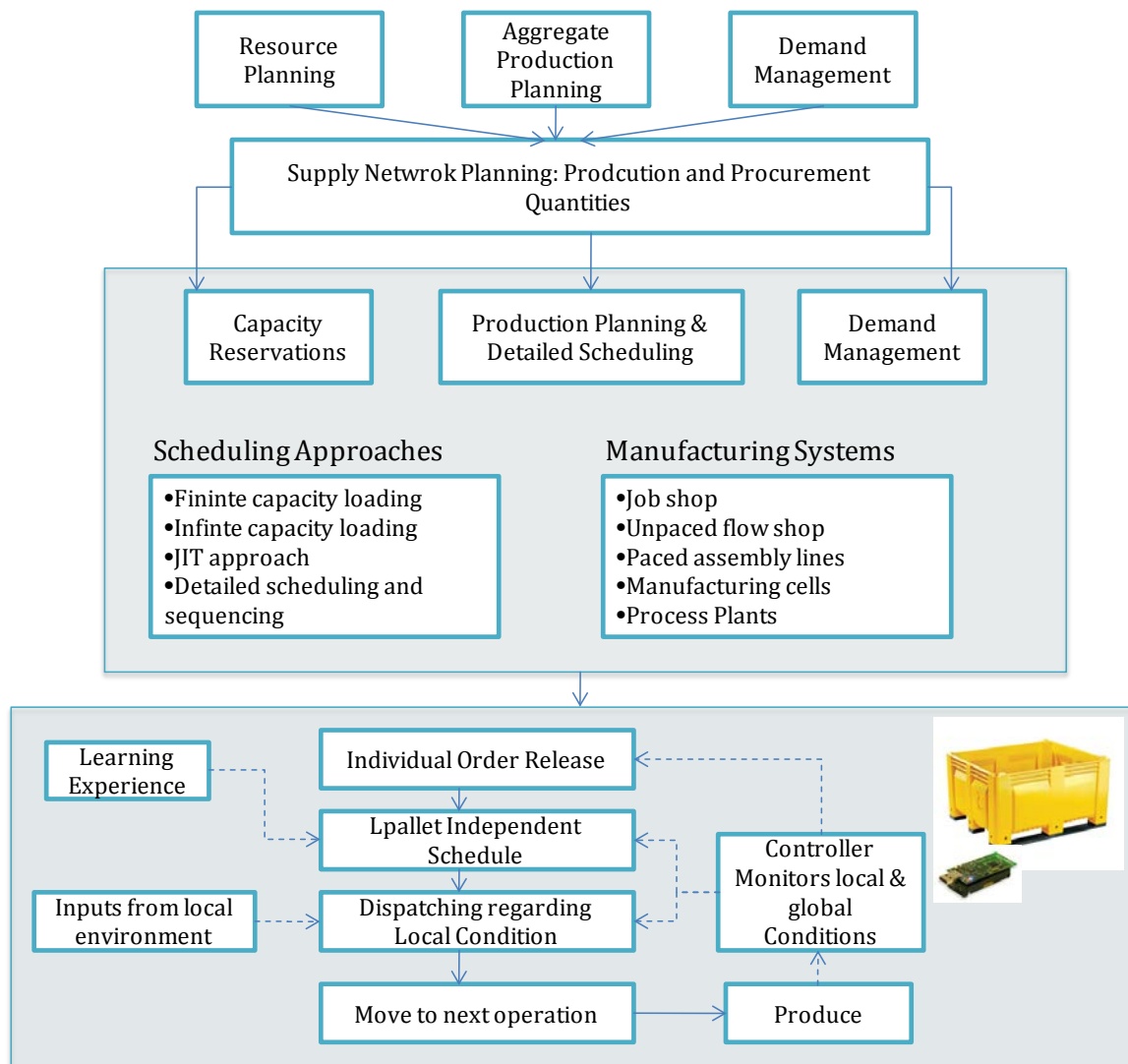


Figure 32: Conventional production planning, scheduling and execution process flows and its interaction in APS, adopted from [69].

Figure 32 depicts Lpallets in shop-floors' decision making and execution in relation to the higher aggregated planning and scheduling levels, as conventional processes. With respect to the state of the art in ICT and computation, it is assumed that each Lpallet has an integrated controller. This controller is assumed to be an active sensor with computation memory, which has the capability of making wireless communications. Such sensors are currently known as WSN. Additionally, in the final part of the current study WSN are integrated into prototypes of Lpallets to have a short real-life experiment above simulations. Figure 33 illustrates the performance of Lpallets within a heterarchical operational level at shop-floors. Here, the interaction of Lpallets with other autonomous objects and conventional planning and control packages (APS/ERP) is symbolically shown. However, it is quite important to know that today MAS in autonomous manufacturing and logistics processes has a crucial role and made several advances in developing autonomy. Nonetheless, this technique of autonomy which is derived from rendering decisions based on negotiation, is not covered by the current study, since this is widely explored in CRC 637 research cluster, for more information see Schuldt [128] as well as www.sfb637.uni-

bremen.de. It is noticeable that the study and performance of Lpallets are quite compatible and even supplementary to MAS, so that they are not mutually exclusive or in parallel at all times.

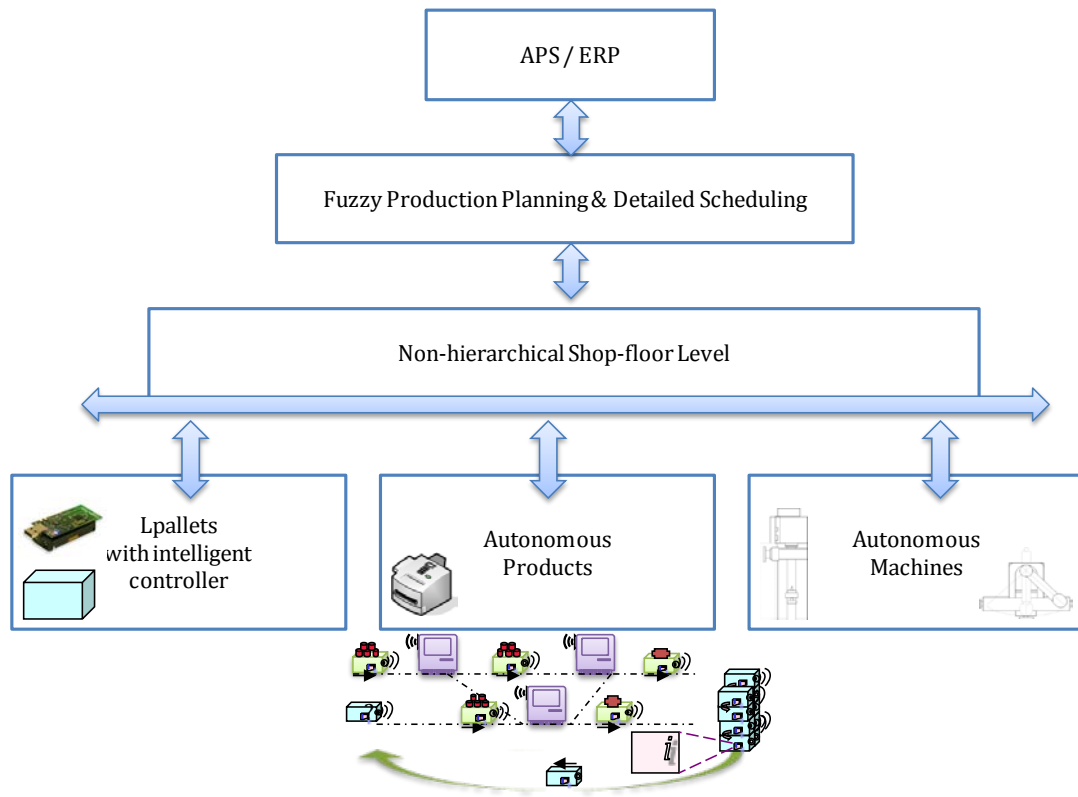


Figure 33: Performance of the assumed Lpallets in shop-floors and their interactions with other equipments and ERP system.

Furthermore, in the current study, it is tried to assume a quite simple performance procedure for Lpallets, since the concept is in its infancy period. *Generally, the performance procedure in Lpallets initiates with some criteria chosen for inputs and outputs of Lpallets.* As material flow control is the main task of Lpallets, as autonomous logistic objects, the conventional metrics for evaluating a smooth and productive logistic system are considered. Among all are utilization of machines (working stations), level of WIP, throughput time (TPT), responsiveness, for more information see Gunasekaran *et al.* [266], Wiendahl *et al.* [267], and [63].

So, each of the metrics solely or simultaneously can be entered as input(s) into each controller of Lpallets. Once the inputs are entered the controller of an Lpallet starts to map them to logical outputs as the decision of the respective Lpallet for the moment. Moreover, for each of the metrics, a target function can be chosen as objective or fitness function in the controller. Based on the objective functions and regarding the type of controller the decisions reflect levels of autonomy and intelligence in performance.

However, in this study, just neural network, simple little's law, and fuzzy controllers are examined as alternative controllers concerning the complexity of inputs and outputs for

Lpallets and operating environment, see Figure 34. These experiments and results are all given in the experiments' chapter.

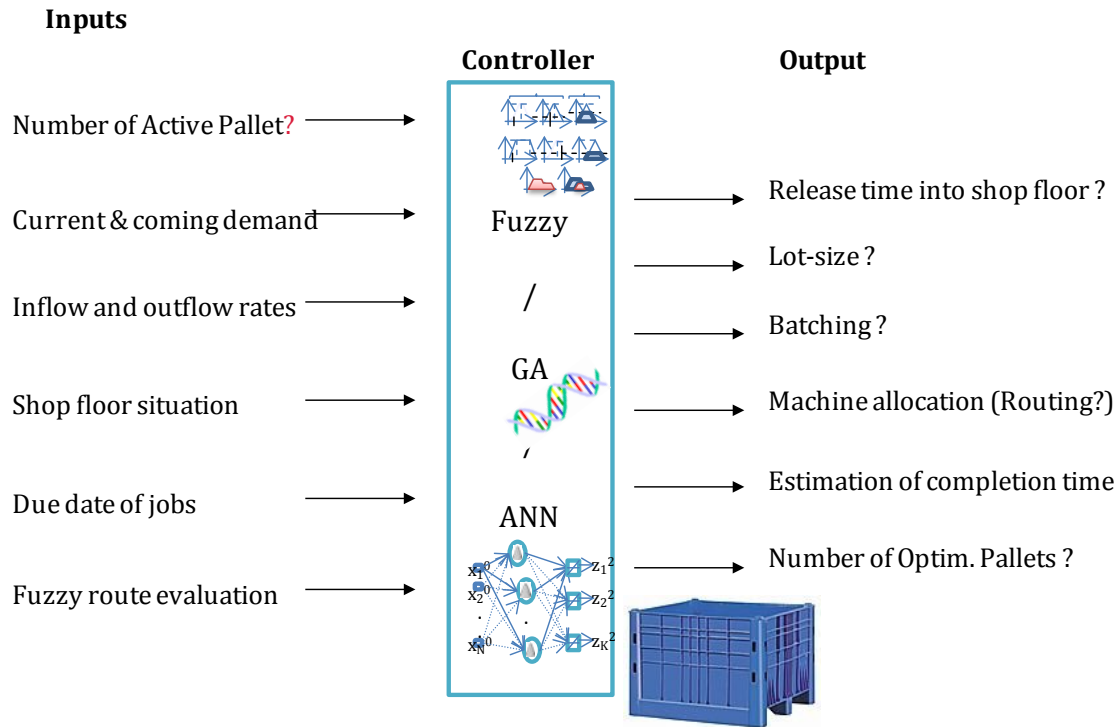


Figure 34: Symbolic input, controller, and output of Lpallets.

In summary, according to the definition of autonomy each object has the merit of decision making by itself in an equality circumstance. Thus, autonomous pallets, in this context, seem to be assisting tools for the individualization. Besides, learning can be a method to convey autonomy to decision makers (Lpallets represents this fact). However, the notion of Lpallets is not limited to pallets. It may cover any similar objects to pallets, which have the ability to carry a limited number of products at outbound as well as inbound (production lines), e.g., bins, boxes, crates, fixtures. Furthermore, pallets have some unique advantages to become a responsive candidate for autonomous controlled logistics object. These benefits can be displayed, for example, by specific material flow controls like pull systems. Lpallets bring several advantages in conventional logistics environments as well as those with autonomy. Indeed, the flexibility and adaptability of Lpallets as autonomous objects can comply with the required specifications of several new emerged strategies in production and logistics. For instance, a direct application of Lpallets can be in mass customized manufacturing systems with various individual processes for each product. Thus, the vicinity of pallets (fixtures, bins, or alike) as the first tier of conveyance means and direct treatment with individual products suits the Lpallets to be employed in highly customized environments. It is noticeable that each of the discussed issue pertinent to Lpallets' concept, development, and application, are broadly explained in the next sections.

4.2 Artificial Intelligence

Over the last few decades, artificial intelligence (AI) has become a leading-edge technology with breakthroughs in several engineering applications. Originally, the concept AI was initiated in computer science with the aim of imitating human intelligence and expertise, by means of intelligent machines. It mainly focuses on intelligent computer programs that are central to intelligent objects. This is why the artificial adjective is given to this type of human-made intelligence. In other words, AI is the capability of doing special things by machines that accomplishing them require intelligence by human. Millington *et al.* [268] pp 4 define AI as something which “is about making computers able to perform the thinking tasks that humans and animals are capable of”. Besides, they assume a threefold distinction for AI by three types of researchers’ interests. The distinction includes philosophy (understanding the spirit of intelligence), psychology (insight in mechanism of the human brain and mental process), and engineering (developing algorithms to imitate human-like tasks). Munakata [269] introduce AI as prospective substitution of human intelligence. He explains AI as “the study of making computers do things that the human needs intelligence to do”. He also considers intelligent computation as complement of AI. The work highlights the issue that after the industrial revolution to substitute human muscle with machines, AI is going to replace human intelligence with machines.

Accordingly, intelligence is translated by Engelbrecht [270] pp 3 as “the ability to comprehend, to understand and profit from experience, to interpret intelligence, having the capacity for thought and reason”. Additionally, he lists some other attributes like creativity, skill, consciousness, emotion and intuition to describe this term. Wang [271] defines intelligence as “the overall capacity of the individual to act purposefully, to think rationally, and to deal effectively with the social and cultural environments”. As Fogel [272] expresses, intelligence is “the capability of a system to adapt its behaviors to meet its goals in a range of environments”. Besides, Negnevitsky [273] talks about intelligence as “the ability to learn and understand, to solve problems and to make decisions”. Conclusively, intelligence has some key features as logistical decision making, learning, and being purposeful. Correspondingly, intelligence achievement is a consequence of evolution. In this regard, during the evolutionary process towards intelligence the fact of learning by doing emerges. Indeed, this importance has led to survival of intelligent creatures [273].

In the same way, machine learning is a branch of AI that employs several methods of computational intelligence to realize intelligence in human-made objects, by means of learning. Actually, learning allows machines to enhance their perspectives to the environment and improve their performances by means of profiting from experience. Additionally, machine learning is defined as a tool for data mining, and even they are sometime equally used like in [274] pp 4, [275]. However, computational intelligence is the core of AI, which encompasses all methods and algorithms that comply with absolute or partial achievements in the intelligence target, see also Wang’s taxonomy of abstract intelligence [271]. However, among the techniques and tools for realizing AI, are ANN, evolutionary computing, and fuzzy systems [269] pp 2.

According to Anderson *et al.* [276] pp 4, learning is a strong tool for getting insight into studies of AI. Therefore, it is at utmost importance for such researchers to understand the nature of learning and to implement this merit on machines. Besides, they review learning as an ability of a system to do similar tasks more effectively after some experiences, which lead to adaptive changes and modifications in the system's perception. Moreover, the Importance of learning knowledge for intelligent agents is addressed by Poole *et al.* [277] pp 11, and Ramos *et al.* [275] as well. Besides, the modularity approach for the sake of simplicity is addressed here. This is quite relevant to the topic of this work in solving complex problems like logistics. Indeed, learning is a process of rendering decisions and improving them over time. So, decision making can be an attribute of the process of learning as well as intelligence. According to Millington *et al.* [268] pp 10, decision making is a process of elaborately defining what to do next for a decision maker. Furthermore, for making decisions an intelligent object must have a strategy (policy).

In addition to ANN— as the famous intelligent methods for learning— and fuzzy systems— as intelligent decisions support systems— there are some other techniques with learning capability. Among which are some algorithms with greedy features to solve optimization problems, which are classified into meta-heuristic algorithms as well. In fact, the greedy attribute of such causes stepwise local improvements towards global optimum. So, these algorithms are also known as global optimization algorithms with an iterative procedure [278], e.g., GA, SA, and tabu search. According to Weise [278] “A heuristic is a part of an optimization algorithm that uses the information currently gathered by the algorithm to help to decide which solution candidate should be tested next or how the next individual can be produced. Heuristics are usually problem class dependent”. Accordingly, he explains meta-heuristic as “a method for solving very general class of problems. It combines objective functions or heuristics in an abstract and hopefully efficient way, usually without utilizing deeper insight into their structure, i.e., by treating them as black-box-procedures”.

Consequently, several technologies are already introduced to the procedure of realizing AI into intelligent systems. Among which are expert systems, ANN, fuzzy systems, and evolutionary computation, see [273]. In the current work ANN, fuzzy systems, and evolutionary computation are discussed with more details and employed accordingly. Indeed, evolutionary computation (algorithms) encompasses several techniques that amongst them, GA, simulated annealing, and tabu search are briefly expressed below.

4.2.1 Genetic Algorithm

GA is the most popular evolutionary algorithm with global search approach towards finding global optimum or near global optimum solution between a wide range of possibilities [278]. It is primarily developed in the mid of 1950s when some computer scientists and biologists started to employ computers to analyze genetic processes and evolution in the nature [279] [280]. The algorithm is recognized as meta-heuristics with a broad application's scope for different problem dependent disciplines, e.g., engineering, medicine, biology, sociology. Moreover, GA resembles the natural behavior governing the survival mechanisms in the nature by means of evolution. In fact, biological species in the

nature have overcome the challenges of randomness (chance), nonlinear behaviors in interactions, and temporality leading into chaos, by means of evolution in genes [281] pp 1. As these challenges are also common in every optimization problem, evolutionary algorithms are suitable for practical applications. However, there is no guarantee for achieving the optimum solution by means of GA, since there are several stochastic parameters affecting the quality of GA, like other meta-heuristics [281] pp 36, [278] pp 60. For instance, in addition to fitness function, GA has some operators as selection, crossover, and mutation that directly influence the performance quality of this method in finding better solutions within step-wise improvements in local solutions. Nevertheless, GA is suitable for complex problems with *NP-hard* and nonlinearity attributes that are usually impossible or very time consuming to be optimally solved by conventional solutions in OR, e.g., simplex. It has been shown that GA is able to find optimum or near optimum solutions within a fairly quick time by means of dismissing (hopefully) non-improvable variants in the solution space G [235].

Generally, GA seeks for the solutions between the elements of *genotypes* in the space of *genome*. In the nature, genotypes— also called chromosomes or individuals— carry the hereditary information of an organism encoded in its DNA. Indeed, optimization process of GA starts by randomly generating a population of solutions (individuals), which each solution is in the format of genotype. The characteristics of a solution of an optimization problem are basically stored in one or more chromosome(s). In this regard, a chromosome is made of an ordered sequence of single genes in a linear manner. The position of a gene in a chromosome is called *locus* and its content is named *allele*. Each gene in the chromosome carries a single parameter of a coded solution (genotype). Thus, a genotype conveys a complete coded solution in DNA, which in order to find the original solution of that it must be decoded into its phenotype [282], see Figure 35. In other words, a solution instance of a problem is originally in a phenotype description that in GA for facilitating the search process it is decoded into a chromosome description (genotype). Mostly, to codify the solution of a problem, binary-based encoding procedure is selected. Nonetheless, encoding is not limited to binary values in strings, but integer or real numbers in the form of vectors can be used too [278] pp 145.

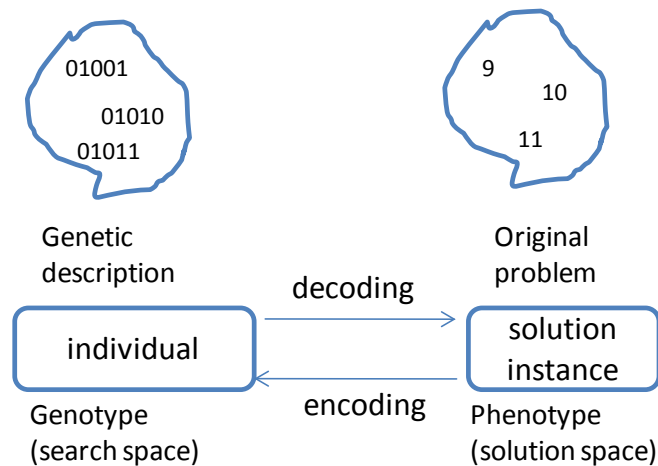


Figure 35: Encoding / decoding of a solution [282] pp 55.

Initially, GA produces a population of random individuals (solutions) in the first generation, and then this population is iteratively replaced by a new population of individuals in each new generation, till the termination condition is met. In fact, individuals in each new generation are bred by the selected individuals (parents) in the previous population by means of genetic operators like in the nature. Accordingly, the genetic operators derive the evolution in populations. They include recombination (of two parents) by means of crossover as well as reproduction (of a single) by means of mutation, permutation, or inversion. It is also likely to have both operations consecutively in order to breed new (diverse) children with differences to the parents. Therefore, the genetic operators, selection process, and termination condition have direct effect on the quality of the GA results [278] pp 147.

Mutation: is a crucial operator in preventing GA to trap in a local optimum. It preserves the required diversity of individuals (solutions), as expected from this algorithm. Mutation like in the nature, which has led to better creatures tailored to their environments, causes some random changes in the genotypes. This randomness can be applied to the values (allele) of n genes $0 < n < \text{length}(\text{of gene})$ to be changed at once. Moreover, if the chromosomes' alleles are binary values then they can easily get toggled, while for real numbers they may be changed by use of the normal distribution with the average value of that number, see Figure 36.

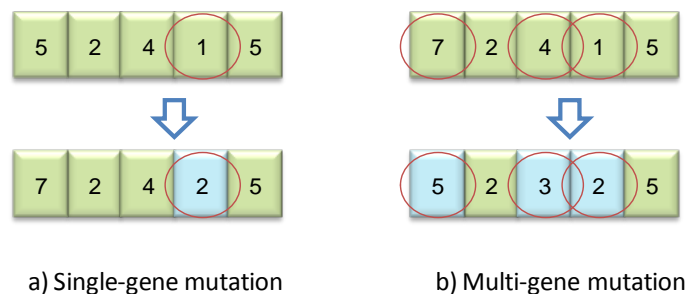


Figure 36: Mutation by means of alternating alleles.

Permutation: is a matter of reproduction in GA. Sometimes it may be seen similar to mutation, since the both devise random change to genes. Now, permutation does this randomness to the locus instead of allele. It means the positions of genes in a chromosome are randomly changed or similarly saying two genes exchange their alleles with each other, see Figure 37. For instance, this can be used for sequencing problems, which is the matter of the current work with Lpallets.

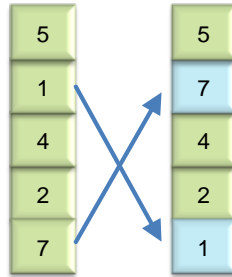


Figure 37: Permutation of two genes.

Crossover: is the main operator (recombination) of GA as well as the main player in the nature. The recombination operators (variants) rarely happen to organisms, but crossover is very common habit of the nature. Thus, this operation performs as driving engine for GA. The simple procedure of crossover is just swapping one or more part(s) of two individuals (parents) to breed a child (offspring) or two children, see Figure 38.

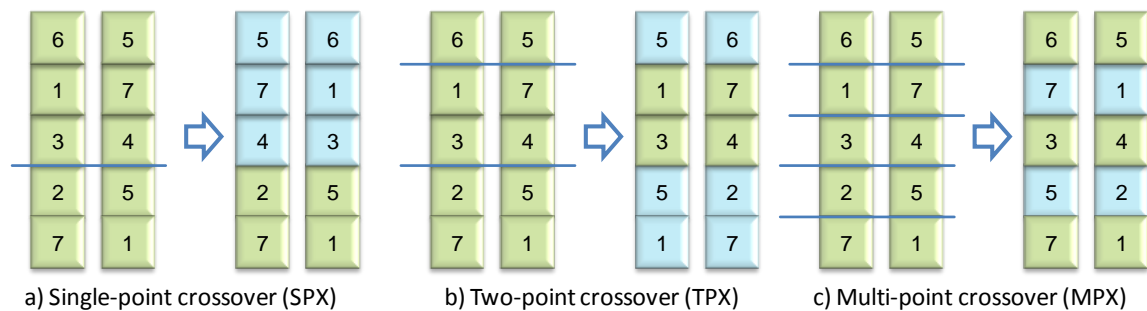


Figure 38: Simple variants of crossover operation.

However, there are some specific variants of crossover, which may be used in special cases. Among which are: *OX* (order crossover), *PMX* (partially matched crossover), and *CX* (cycle crossover) [283]. In *PMX*-crossover two points in each parent chromosome are randomly chosen, and then just the genes between both points of each chromosome are exchanged. Yet, the process is not finished. It should be further looked if the other genes, which are not exchanged, have similar values as exchanged genes in that respective chromosome. If this is the case then the repeated genes are changed by their counterparts regarding the exchanged genes, see Figure 39.

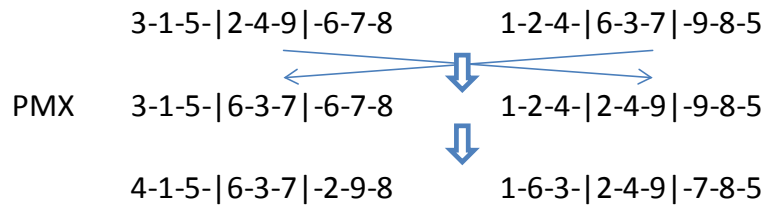


Figure 39: PMX-crossover.

In OX-crossover again two points randomly cut the chromosome of each parent. Then the same as PMX the bounded genes are exchanges to each offspring, while the rest positions of the genes in each chromosome are filled by the not repeated genes of the corresponding parent starting from the second cut-point, see Figure 40.

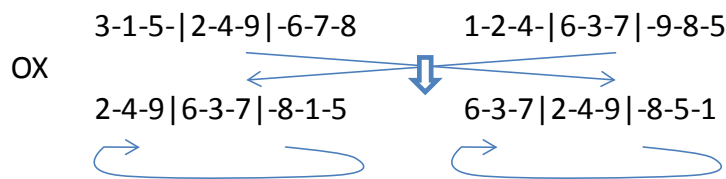


Figure 40: OX-crossover.

Contrarily, CX operator is a bit different and has no cut point. Instead, the position of each gene in each offspring should be inherently chosen from either parent. It means, for example, starting from the first gene of a parent to make the first gene of a child causes the second gene to be chosen from the second position of another parent. However, since the first position is occupied then the gene with the same value should be chosen again from the first parent. And this procedure continues alternatively to breed the first child. The second child is bred by complementary cross as well, see Figure 41.

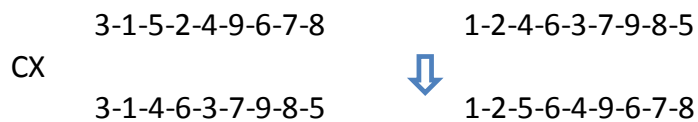


Figure 41: Cycle crossover (CX).

In addition to the mentioned variants, there are some other cases which are pertinent to variable string length of chromosomes. However, they are not very relevant in the current work. Furthermore, before inserting any type of GA operations to render a new population, the individuals in the current population must undergo an evaluation and selection process. In other words, in a problem first the contribution of each individual (solution) in a population to the objective function—called *fitness function* in GA— must be evaluated. After estimating the quality of each individual (fitness value), according to a specific selection procedure, each individual may get a proportional probability to be chosen as a parent of the next generation. However, the goal of the selection process is to choose the fittest individuals to be selected, distinct from the existing various selection procedures. The universal algorithm of GA can be simply displayed by Figure 42.

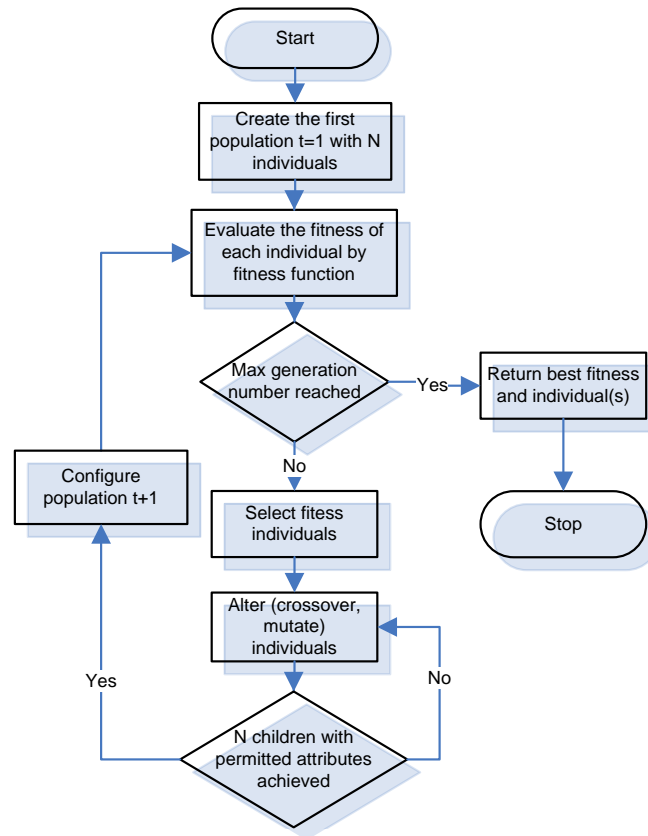


Figure 42: Simple flow chart of GA.

Moreover, there are several selection processes which each of them may cause diverse generations in an alternative manner. Some selection procedures include truncation selection, roulette-wheel selection, tournament selection, ordered selection, stochastic remainder selection, stochastic universal sampling, see [284]. However, some of which look easy and some have more sophisticated functions. In the current work just the famous and traditional one of them, as roulette-wheel selection, is introduced and applied. This is because of its simple procedure (function), fair performance, and abundant use in academic papers, see, [285] pp 20.

Roulette-wheel selection intends for fitness maximization. Here, each individual proportional to its fitness value gets a chance to be selected as a parent of the next generation [278] pp 124 and [286]. According to (2.2.1), individuals are selected and added to mate pool to breed a new generation. The procedure of this selection method is as follows: each individual between others may fill part of the Rolette-wheel (probability wheel) based on its probability. It is noticeable that the entire area of the wheel equals one. Then the wheel rotates for some random rounds and stops afterwards. Wherever the pointer shows is the individual to be selected, see Figure 43.

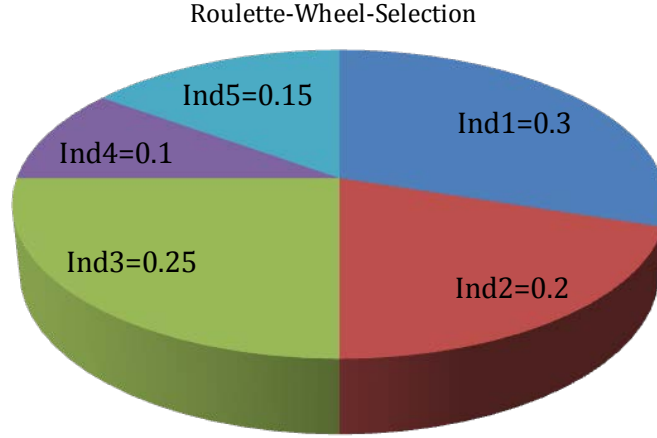


Figure 43: Roulette-Wheel-Selection for individuals.

$$P_i = \frac{f_i}{\sum_{j=1}^N f_j} \quad (2.2.1)$$

where P_i is the probability of i^{th} individual to be selected, $j = \{1, 2, \dots, N\}$ is the counter of individuals in a population. Accordingly, for minimization problems and in order to homogenize the results out of this fitness proportionate selection it is better to normalize the fitness values of individuals according to (2.2.2), which lead to (2.2.3) with the minimization target.

$$f_i^{\text{norm}} = \frac{f_{\text{max}} - f_i}{f_{\text{max}} - f_{\text{min}}} \quad (2.2.2)$$

$$P_i = \frac{f_i^{\text{norm}}}{\sum_{j=1}^N f_j^{\text{norm}}} \quad (2.2.3)$$

It is noticeable that although GA has had several achievements in solving complex problems, but its ordinary algorithm does not always lead to an optimum solution, in limited time. Missing and premature convergence and infeasible solutions (individuals) are the threats of the general form of GA [287]. Therefore, some local adaptations and modifications could be integrated to the procedure of producing individuals in order to evade inefficiency and improve the optimum problem search. In this case, GA is recognized as Memetic algorithm (MA) [288]. In an optimum seeking search, MA tries to evaluate different methods of selection, crossover and mutation, with the target of achieving the best solution in a confined time horizon. However, this is not covered by the current study.

4.2.1.1 Contribution of GA to Lpallets

It can be comprehended in every single Lpallet within a decentralized manner. Besides, GA can be used as a central controller to authorize the best sequencing of operations by means of global monitoring and allocating pallets to operations. For instance, in the decentralized manner, each Lpallet, assuming to circulate in an assembly line, develops a population of individuals (operations' sequences) and examines them in several rounds. For example,

regarding the dynamic circumstance of assembly lines with customized operation sequences, the GA of each Lpallet breeds new individuals (operations' sequences) according to its specific fitness function (e.g., flow time) during the periods. However, exploitation of GA for Lpallets towards learning the behaviors of a system is subjective and may have different models. This issue is discussed later in experiments chapter in detail.

4.2.2 Simulated Annealing

SA is a meta-heuristic algorithm for finding (near) optimum solution within an iterative procedure. The procedure of this method is copied from a physical process in statistical mechanics in which metal crystals reconfigure and get equilibrium during annealing process [278]. As a global optimization algorithm SA is suitable for combinatorial problems with huge solution spaces, function optimization, machine learning, networking and communication, etc. Unlike to GA, SA algorithm starts with a single initial solution (individual) and proceeds with unary search mechanism. SA is similar to GA in meta-heuristics with small differences in its procedure. Basically, if the population size in GA is only one then it resembles SA. Thus, in every iteration, the current solution is the only chromosome in that generation. In this manner, no crossover can be happened with one individual but only mutation. In fact, this is the major difference between SA and GA. Obviously, a new solution in GA is the result of combining two different solutions, while SA brings a new solution by adjusting the previous single solution with a local move. However, the performance quality of GA and SA depends on the problem and the representation.

Moreover, annealing process in metallurgy is addressed by that procedure in which metal properties changes to desired ones. In other words, annealing is a heat treatment process in which a hot metal slowly cools down in order to relocate metal crystals towards a tidy arrangement. In order to increase the energy of ions heating the metal is the start of this process, and then during the cooling procedure the structure of the crystals gets rearrangements till an equilibrium state in the metal is achieved. However, the cooling schedule, which defines the initial temperature of the metal and the cooling speed, plays an important role in the final quality of the metal in terms of hardness and, etc. Otherwise, the system gets trapped into a local minimum of energy and non-crystalline state.

Accordingly, the annealing procedure is simulated by SA in order to find the optimum solution for a problem in which several local solutions exists on the cooling way. After each level of cooling in annealing process the energy level of atoms decreases and then a new geometry of an atom by means of randomly displacement is achieved (a new solution). Here, the level of energy E (objective function) with new geometry is compared against the previous one and their difference is computed by $\Delta E = E_{new} - E_{old}$. Then the probability of accepting this geometry $P(\Delta E)$ is calculated by (2.2.4).

$$P(\Delta E) = \begin{cases} \exp\left(-\frac{\Delta E}{T}\right); & \text{if } \Delta E > 0 \\ 1 & ; \text{otherwise} \end{cases} \quad (2.2.4)$$

If the new neighbor geometry (solution) has less energy than the previous one, then this transition is accepted, otherwise it can be accepted by probability of $P(\Delta E)$. This procedure iterates till the final temperature is reached. Eventually, at the specific temperature T_{min} the system hopefully gets into the global minimum energy. The abstract form of SA algorithm is depicted in Figure 44.

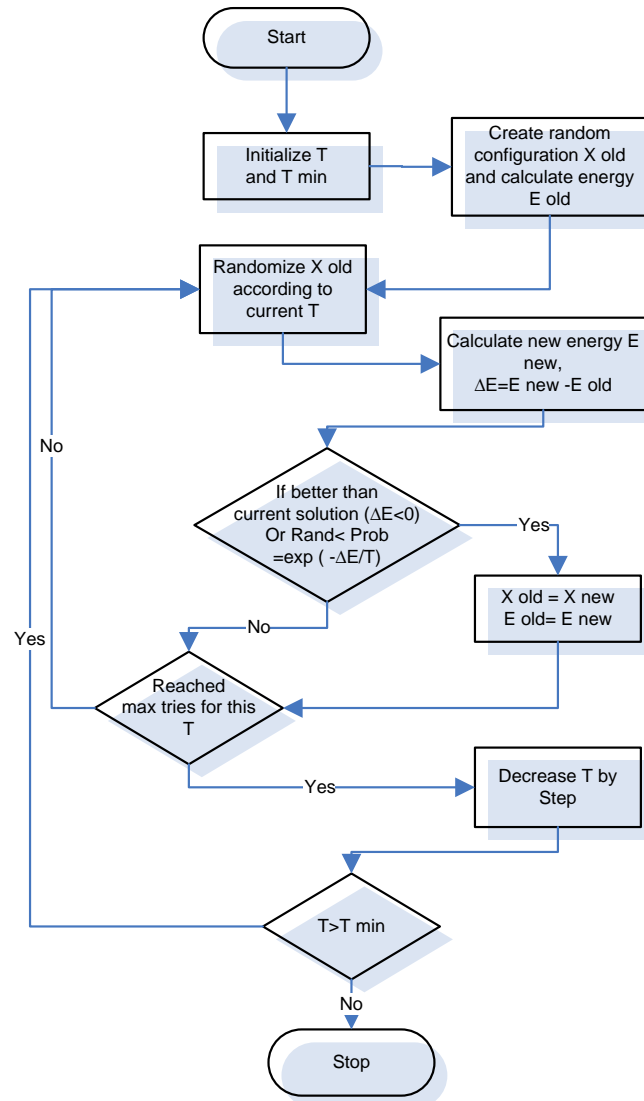


Figure 44: General flow chart of simple simulated annealing algorithm.

Moreover, the cooling schedule is the most important factor in the quality of the algorithm, since fast cooling leads to a local minimum (no convergence guarantee) and slowly cooling may exceed the duration of a full exploration of all solutions. Therefore, specific attention has been paid to this issue in SA and respectively several strategies are already developed. This schedule is shown in the flow chart (Figure 44) by step decrease of temperature T . Nevertheless, since simplicity of calculation is the key factor in realizing autonomy with learning and intelligence capability, in this work the simple calculations are undertaken. Two simple strategies from the book of Weise [278] pp 266, are adopted for this purpose as follows:

- After each maximum tries (iterations) m for a current temperature T reduce $T \xrightarrow{to} (1 - \epsilon)T$, where $m > 0$ and $0 < \epsilon < 1$ are empirically defined,
- Given a total number of iterations K for the entire algorithm, after each maximum tries m temperature T reduces to $T \xrightarrow{to} T_{start} \left(1 - \frac{t}{K}\right)^\alpha$, where t is the iteration number so far and α is a constant like 1,2, or 4 which is rather to be find subjectively.

Furthermore, if the objective function is extended to multi-objective function, the algorithm can be developed by reflecting a set of optimal solutions— instead of one— by making tradeoffs between the objectives. This can be achieved by assuming the multi-objective function as a fitness assignment process, for more information see Weise [278] pp 267.

4.2.2.1 Contribution of SA to Lpallets

It can be realized in each single Lpallet where its objective function in each cyclic round returns a value representing the energy of the current geometry (solution) chosen by the Lpallet. Then this value undergoes the algorithm to define other parameters towards the global solution. However, the dynamisms of the logistics environment make the algorithm keep generating new solutions continuously. In the regard, the conventional SA may be useful in logistic environments with not very transient circumstances. Otherwise, SA performs like random decision procedure. In this work, because of similarities between GA and SA, it is not widely applied except a minor example in the experiments' chapter to justify the results out of GA in offline solution search. Nevertheless, in further works it has to be adjusted for single Lpallets.

4.2.3 Tabu Search

Appropriately, tabu search is considered as a global optimization meta-heuristic algorithm that was initiated in the mid of 1980s by Glover [289]. It is principally a simple and effective technique for such optimization problems. The specification of this algorithm is the *tabu* list of visited solutions, which generally avoids redundancy in the algorithm (visiting local optimum), while ignorance of good visited solutions can be prohibited as well. In doing so, the respective tabu list, which collects the already visited solutions, has a finite capacity of n . Indeed, the procedure is like other global search algorithms that stepwise seek for new solutions. It starts with an initial (feasible) solution and iteratively produces new improved solutions by means of randomly moving to a new neighborhood. Then if the new emerged solution is already kept in the tabu list it is immediately neglected, otherwise its contribution to the objective function is evaluated. Then it will be recorded in the tabu list. Accordingly, right after visiting the $n + 1$ solution the first visited one as tabu leaves the list and becomes again authentic to be evaluated by the objective function as a new solution. The general flow chart of algorithm is displayed in Figure 45, for more information see [278] pp 274 and [290].

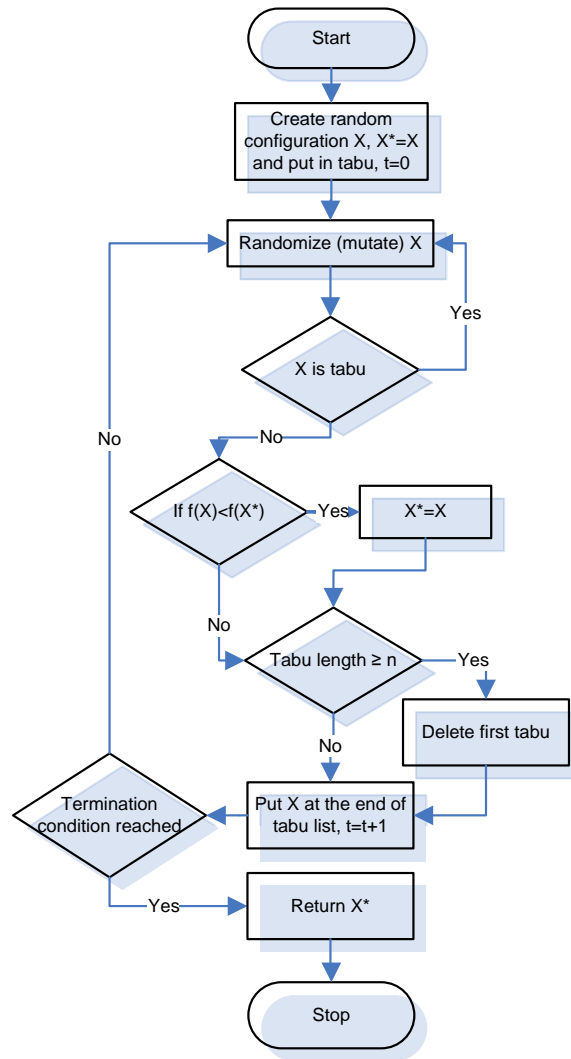


Figure 45: Simple flow chart of TS algorithm.

In the algorithm, X represents the solution and $f(X)$ returns the value of the objective function (fitness). However, the mutation process, the length of the tabu list, and the termination condition can be subjectively selected.

4.2.3.1 Contribution of TS to Lpallets

It can be applied in a single L Pallet as GA or like swarm intelligence. So, like GA and SA it can be used in centralized as well as decentralized problem-solving contributions. However, since the general performance of tabu search is similar to GA and SA in single Lpallets, application of tabu search is recommended as further works.

4.2.4 Fuzzy System

Nowadays, the great interest for precisely solving practical problems is continuously increasing. However, to proceed with this ambition more details of information are required, which are not normally available. In this regard, fuzzy set theory is initially introduced by Zadeh [291] to make a breakthrough in machine understandings about uncertain and incomplete systems. Generally, fuzzy systems (controllers) are those systems with uncertain/imprecise inputs— as fuzzy sets— which approximate outputs

with continuous transition. As Zimmerman [292] states, fuzzy set theory reflects a strong mathematical framework that can analyze and characterize vague conceptual phenomena. Accordingly, limited capacity of human memory or technical systems causes incompleteness in the perception process of environment. This shortcoming, to some degree, can be solved by using fuzzy systems.

Basically, the performance of such systems is based on fuzzy logic with the purpose of extending the classical logic (with crisp and distinct values, e.g., yes/no, true/false, and zero/one). In this manner, fuzzy logic is a multi-value logic with continuous values between $[0\ 1]$ for qualifying the existence of true or false. This specification makes fuzzy logic suitable for imprecise and approximate judgments [269] pp 122. For that reason, processing of inputs in fuzzy systems can be accomplished by the concept of fuzziness by means of using fuzzy rules. This is discussed here later.

In addition, this capability gives rise to fuzzy decision makings appropriate to vague, ill-defined, and complex problems. For instance, in optimization problems with limited/incomplete knowledge one can exploit fuzzy logic to approximately solving obscured problems in a proper way. There is a well-known sentence from Zadeh [293] to explain the appropriateness of fuzzy theory in practice due to vagueness; he says “as the complexity of a system increases, our ability to make precise and yet significant statement about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics”. Accordingly, practitioners have seen that any human-centered problem has, to some degree, uncertainty in its nature [179]. In this manner, fuzzy logic embedded in fuzzy systems can be applied to several practical applications as engineering, medicine, temperature control, electric current control, AI, robotic, and aerospace [294] pp 44.

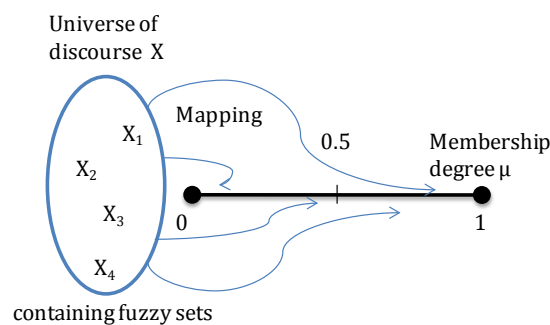


Figure 46: Schematic mapping of member of fuzzy sets to membership degree with $[0\ 1]$ certainty.

Conventionally, the traditional set theory considers each element either as part of a set or apart from that with true or false logic (white/black), in addition to the abrupt transition between crisp values. For instance, this holds true for binary values with being either 0 or 1. However, this precise reasoning is not always practical in the nature and specifically in those processes with human interventions. The classical reasoning may miss some part of knowledge by ignoring the intervals between crisp facts. In contrast, human usually has an approximate understanding of a logical discourse with imprecise terms, which is believed

as an intelligent attribute. Consequently, human is able to roughly comprehend complex systems without getting a complete insight into their intricate relations. So, similar to the way of human to formulate practical problems with qualitative perceptions, e.g., linguistic terms, fuzzy system is able to comprehend such descriptions about problems and to infer them by (map them to) quantitative measures. This ability of approximation is not limited to fuzzy systems, but, for example, ANN reflects the same technique. However, fuzzy systems can facilitate “a more transparent representation of the systems under study, which is mainly due to the possible linguistic interpretation in the form of rules” [295].

This approximate reasoning is the consequence of fuzzy logic with allowance of uncertain judgments. Indeed, it can deduce new elements between ordinary sets with some degrees of certainty, but not an absolute one. However, this brief definition of fuzzy sets is in contrast with the characteristics of ordinary sets. In fact, each of the mentioned elements belongs to fuzzy sets with a certain degree of certainty [270] pp 10. Likewise, the dependency of fuzzy values to a set is represented by their membership values. Besides, membership values are accordingly reflected by the respective membership function $\mu_{\tilde{Y}}$ of the set \tilde{Y} . In this regards, fuzzy set can be mathematically described as follows [296] ch. 2:

Definition 3.2.4.1: If X is a space with generic elements of x , and $\mu_{\tilde{Y}}: X \rightarrow M \subseteq [0,1]$ is the characteristic function that maps X to membership space M . Then the following set of pairs uniquely represents a fuzzy set, see Figure 46.

$$\tilde{Y} = \{x, \mu_{\tilde{Y}}(x) | x \in X\} \quad (2.2.5)$$

where $\mu_{\tilde{Y}}$ is the membership function of the fuzzy set \tilde{Y} to define the membership degrees in that set as $\mu_{\tilde{Y}}(x) \in [0, 1]$. If $M = \{0,1\}$ then \tilde{Y} is changed into a crisp set. And if the membership function of the maximum value in the fuzzy set \tilde{Y} equals to 1 then this fuzzy set is called normal: $\sup_{x \in X} \mu_{\tilde{Y}}(x) = 1$. Accordingly, a fuzzy number can be described as follows [297] pp 3:

Definition 3.2.4.2: A fuzzy number \tilde{Y} is a fuzzy set of the real line with a normal, (fuzzy) convex and continuous membership function of bounded support.

where if \tilde{Y} is a fuzzy subset of X . Accordingly, the support of \tilde{Y} , denoted by $\text{supp}(\tilde{Y})$, is the crisp subset of X which all of its elements have nonzero membership degree in \tilde{Y} .

$$\text{supp}(\tilde{Y}) = \{x \in X | \mu_{\tilde{Y}}(x) > 0\} \quad (2.2.6)$$

Moreover, in a fuzzy number (a convex and normal fuzzy set \tilde{Y}) there exists exactly one real number a with membership degree of one: $\mu_{\tilde{Y}}(a) = 1$. This point a is called peak (center) value of \tilde{Y} .

Definition 3.2.4.3: A fuzzy set $\tilde{Y} = \{x, \mu_{\tilde{Y}}(x) | x \in X\}$ is convex, if for all $a, b, c \in X$ with $a \leq b \leq c$ the following (2.2.7) holds true, see [296] ch. 2.

$$\mu_{\tilde{Y}}(a) \leq \mu_{\tilde{Y}}(b) \leq \mu_{\tilde{Y}}(c) \quad (2.2.7)$$

Definition 3.2.4.4: α -cut set (Y_α) of the fuzzy set $\tilde{Y} = \{(x, \mu_{\tilde{Y}}(x)), x \in X\}$ is a subset of that whose elements have membership degrees equal or bigger than α . Moreover, Y_α returns a crisp set.

$$Y_\alpha = \{x \in X | \mu_{\tilde{Y}}(x) \geq \alpha, 0 < \alpha < 1\} \quad (2.2.8)$$

Furthermore, fuzzy numbers may accept different types regarding the shape of their membership functions, yet by keeping the generality. The membership function can be subjectively (directly) designed or may have some conventional shapes to reflect the type of dependency of fuzzy numbers to their set. So, several shapes can be considered in defining the membership functions of fuzzy sets, among them are triangular, trapezoidal, Gaussian, and s-curve [298] [299] [300]. Below three famous of them are explained.

Triangular fuzzy number (Triangular membership function): is defined by three parameters $\{a, b, c\}$ as follows, see Figure 47:

$$\mu_{\tilde{Y}}(x) = \begin{cases} 0 & ; \quad c > x \text{ and } x < b \\ \frac{(x-b)}{(a-b)} & ; \quad b \leq x \leq a \\ \frac{(c-x)}{(c-a)} & ; \quad a \leq x \leq c \end{cases} \quad (2.2.9)$$

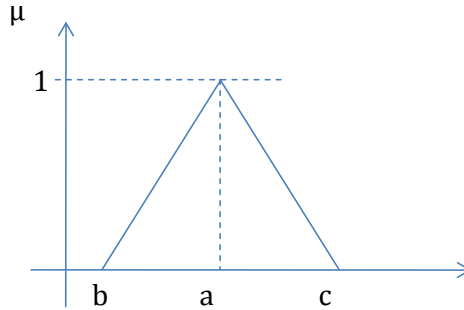


Figure 47: Triangular membership function.

Trapezoidal fuzzy number (Trapezoidal membership function): is characterized by four parameters $\{a, b, c, d\}$ as follows, see Figure 48:

$$\mu_{\tilde{Y}}(x) = \begin{cases} 0 & ; \quad c \leq x \text{ and } x < b \\ \frac{(x-b)}{(a-b)} & ; \quad b \leq x < a \\ 1 & ; \quad a \leq x < d \\ \frac{(c-x)}{(c-d)} & ; \quad d \leq x < c \end{cases} \quad (2.2.10)$$

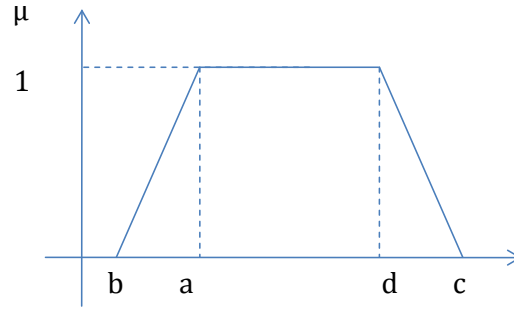


Figure 48: Trapezoidal membership function.

Gaussian fuzzy number (Gaussian membership function): is described by two parameters $\{a, \sigma\}$ like following, see Figure 49:

$$\mu_{\tilde{Y}}(x) = \exp\left(\frac{-(x-a)^2}{2\sigma^2}\right) \quad (2.2.11)$$

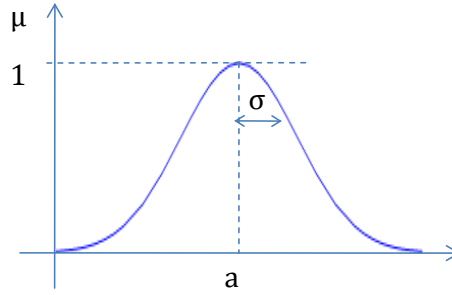


Figure 49: Gaussian membership function.

Moreover, fuzzy systems have some fundamental theories and operations, which are in the core of this theory functionality. Accordingly, there exist some operations on fuzzy sets like other operations in classical sets. The main operations include intersection (AND) as well as Union (OR) which are done according to t-norm and s-norm, respectively [297], see Figure 50. Below some important facts about operations which are relevant to this work are explained:

Intersection: of two fuzzy sets A and B is described by the intersection of their membership functions:

$$\tilde{A} \cap \tilde{B}: \mu_{(\tilde{A} \cap \tilde{B})}(x) = \mu_{\tilde{A}}(x) \wedge \mu_{\tilde{B}}(x) = t[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] = \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)\} \quad (2.2.12)$$

where $t[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)]$ represents the t-norm of the fuzzy sets for intersection.

Union: of two fuzzy sets A and B is described by the union of their membership functions:

$$\tilde{A} \cup \tilde{B}: \mu_{(\tilde{A} \cup \tilde{B})}(x) = \mu_{\tilde{A}}(x) \vee \mu_{\tilde{B}}(x) = s[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] = \max\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)\} \quad (2.2.13)$$

where $s[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)]$ represents the s-norm of the fuzzy sets for intersection.

However, the two operations displayed above are just one type of t-norm and s-norm operations in fuzzy sets. Generally, both of the s-norm and t-norm have some conditions and variants, which are not covered in this work, for more information see [297] pp 8. Only two other relevant variants of both norms called product t_p (algebraic product) and probabilistic s_p (algebraic sum) of sets are as below:

$$t_p(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)) = \mu_{\tilde{A}}(x)\mu_{\tilde{B}}(x) \quad (2.2.14)$$

$$s_p(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)) = \mu_{\tilde{A}+\tilde{B}}(x) = \mu_{\tilde{A}}(x) + \mu_{\tilde{B}}(x) - \mu_{\tilde{A}}(x)\mu_{\tilde{B}}(x) \quad (2.2.15)$$

$$s[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] = 1 - t[1 - \mu_{\tilde{A}}(x), 1 - \mu_{\tilde{B}}(x)] \quad (2.2.16)$$

$$t[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] = 1 - s[1 - \mu_{\tilde{A}}(x), 1 - \mu_{\tilde{B}}(x)] \quad (2.2.17)$$

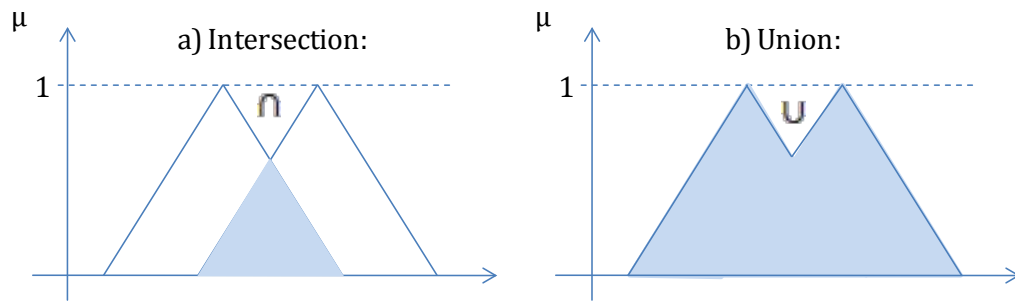


Figure 50: Intersection and Union of two triangular fuzzy sets.

In addition, after the introduction of an important fuzzy set theory called fuzzy (Zadeh's) extension principle [301], several arithmetic operations for fuzzy numbers and relations have become possible. Conventional operations on fuzzy quantities (fuzzy arithmetic) are essentially important for any intelligent system. For example, composition of fuzzy relations out of different spaces can be realized by the composition operator. Among some, the max-min composition operator is the most applied of such. Here, after illustrating the definition of fuzzy relation and extension principle, some important operations are given below.

A general fuzzy relation is a classical relation that for each n-tuple (a_1, a_2, \dots, a_n) a membership degree is considered. Or in other words:

Definition 3.2.4.5: if A and B are two classical sets $A, B \in U$ then fuzzy relation \tilde{R} is a subset of the Cartesian product space from $A \times B$ which is defined as:

$$\tilde{R} = \{[(a, b), \mu_{\tilde{R}}(a, b)] | (a, b) \in A \times B\} \quad (2.2.18)$$

Theorem 3.2.4.1: Let $\tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n$ be independent fuzzy numbers with membership functions of $\mu_{A_1}, \mu_{A_2}, \dots, \mu_{A_n}$ respectively defined on universes X_1, X_2, \dots, X_n . And $f: R^n \rightarrow R$ is a function which maps $X_1 \times X_2 \times \dots \times X_n$ (Cartesian product) to the universe Y . Then according to the extension principle, the fuzzy image \tilde{B} of $\tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n$ can be derived with its membership function $\mu_{\tilde{B}}$ [302]:

$$\mu_{\tilde{B}}(y) = \sup_{x_i \in X_i} \min_{i=1,2,\dots,n} \mu_{A_i}(x_i) \quad (2.2.19)$$

where $y = f(x_1, x_2, \dots, x_n)$ defines the respective constraint.

By having this extension principle other operations on fuzzy relation and numbers become possible, some of which are as follow:

$$(\tilde{A} + \tilde{B})(z) = \sup_{z=x+y} \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\} \quad (2.2.20)$$

$$(\tilde{A} - \tilde{B})(z) = \sup_{z=x-y} \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\} \quad (2.2.21)$$

$$(\tilde{A} \times \tilde{B})(z) = \sup_{z=x \times y} \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\} \quad (2.2.22)$$

$$(\tilde{A}/\tilde{B})(z) = \sup_{z=x/y} \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\} \quad (2.2.23)$$

$$\text{MIN}(\tilde{A}, \tilde{B})(z) = \sup_{z=\min(x,y)} \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\} \quad (2.2.24)$$

$$\text{MAX}(\tilde{A}, \tilde{B})(z) = \sup_{z=\max(x,y)} \min\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\} \quad (2.2.25)$$

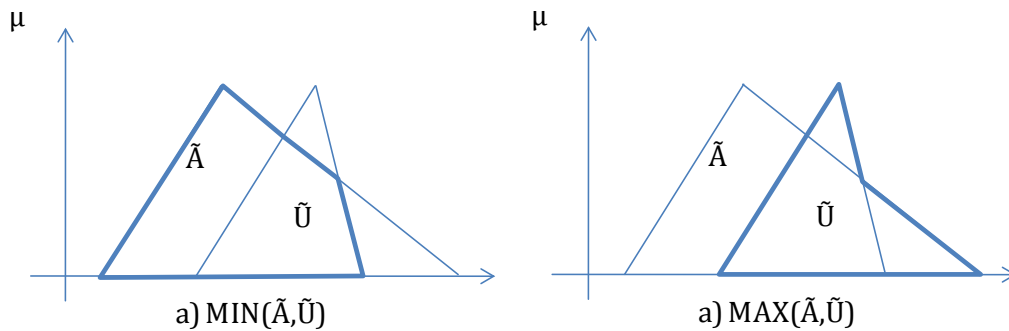


Figure 51: Minimum and maximum of two fuzzy numbers \tilde{A} and \tilde{U} .

Furthermore, some relations conventionally exist on classical logic which some of them holds true on fuzzy logic as well. Among them, logical inference using fuzzy rules is pertinent to the application of fuzzy logic in the current work. It is supposed to employ fuzzy systems with the core of fuzzy logic to render decisions under complex and vague circumstances. Accordingly, by extending the concept of fuzzy inference, this becomes specifically correct for approximate reasoning as a strong framework of fuzzy theory introduced by Zadeh [303] to deal with uncertain and vague information. Nonetheless,

since application of fuzzy operators on fuzzy sets domain is not always straightforward or not known in some cases, IF-THEN knowledge-based rules are quite appropriate for inferring system to be applied by fuzzy systems [297] pp 101.

Moreover, in case of complete information availability about an interaction like $y = f(x)$, interpolation of new relations between two interactive variables is easy to be understood and it can be inference as:

$$\text{if } y = f(x) \text{ and } x = \acute{x} \xrightarrow{\text{then}} y = f(\acute{x}) \quad (2.2.26)$$

Fuzzy knowledge-based systems are quite common systems for inferring and controlling imprecise environments with a simple format as follows.

$$R_i: \text{If antecedent}_i \text{ Then consequent}_i \quad (2.2.27)$$

where $R_i; i = 1, \dots, N$ stands for one fuzzy rule. Accordingly, in fuzzy circumstances incomplete information is unavoidable, so that the use of knowledge-based systems can be a great assistance to make approximate reasoning in fuzzy logic realm. However, more than one fuzzy rule is usually required to infer an approximate reasoning of ambiguous relations, thus, a mechanism is required to aggregate all rules in order to make rough understanding of the relations, for more information see [297] pp 101. Indeed, decision making with multi-criteria is a specialty of fuzzy set theory, so that it provides an apt mean of attractive aggregation connectives for integrating membership values of different criteria bearing uncertain information [297] pp 65.

$$\tilde{R}_i: \text{If } x \text{ is } \tilde{A}_i \text{ Then } z \text{ is } \tilde{C}_i \quad (2.2.28)$$

$$R_i(u, w) = \mu_{\tilde{A}_i}(u) \rightarrow \mu_{\tilde{C}_i}(w) \quad (2.2.29)$$

$$R = \text{Agg}(\tilde{R}_1, \dots, \tilde{R}_m) \quad (2.2.30)$$

where \tilde{A} and \tilde{C} are fuzzy set usually in the form of linguistic terms. Then if aggregation of rules is done by means OR operator, then R can be calculated as:

$$R(u, w) = \cup_{i=1}^m \tilde{R}_i : \mu_{\tilde{R}}(u, w) = \max_i \{ \mu_{\tilde{R}_i}(u, w) \} = s[\tilde{R}_1(u, w), \dots, \tilde{R}_m(u, w)] \quad (2.2.31)$$

Otherwise, if aggregation of rules is interpreted as AND operator then R is calculated as:

$$R(u, w) = \cap_{i=1}^m \tilde{R}_i : \mu_{\tilde{R}}(u, w) = \min_i \{ \mu_{\tilde{R}_i}(u, w) \} = t[\tilde{R}_1(u, w), \dots, \tilde{R}_m(u, w)] \quad (2.2.32)$$

Moreover, this inference mechanism can be simply defined by Figure 52, which is an extended description to the performance of fuzzy inference systems in rendering decisions,

based on fuzzy logic. This mechanism is sometimes called fuzzy associative memory (FAM). In fact, the fundamentals of fuzzy systems are membership functions, logical operations, and IF-THEN rules. Generally, fuzzy inference systems have some variants that two famous ones with rule-based fuzzy models are Mamdani [304] [305] and Takagi-Sugeno [306].

Furthermore, fuzzy systems for inference mechanisms have usually five steps as fuzzification, application of fuzzy operators, implication of antecedences to consequents in fuzzy rules, aggregation of the consequents, and defuzzification [175]. However, after aggregation of rules, defuzzification is the final step of a fuzzy inference system to reflect the ultimate fuzzy value to a crisp value. Defuzzification process has several types, e.g., center of gravity/centroid (COG), weighted average (WA), mean of maxima (MOM), for more information see [307] [308].

$$COG = \frac{\int_a^b x \mu_{\tilde{A}}(x) dx}{\int_a^b \mu_{\tilde{A}}(x) dx}; \text{ for continuous case} \quad (2.2.33)$$

$$WA = \frac{\sum_{i=1}^I x_i \mu_{\tilde{A}}(x_i)}{\sum_{i=1}^I \mu_{\tilde{A}}(x_i)}; \text{ for discrete case} \quad (2.2.34)$$

where $[a \ b]$ is the boundary of the area configured out of consequences aggregation (which is a fuzzy set), I is the number of elements x_i in the discrete domain of X . MOM finds the highest membership function and then finds all points that have this membership degree and takes their average.

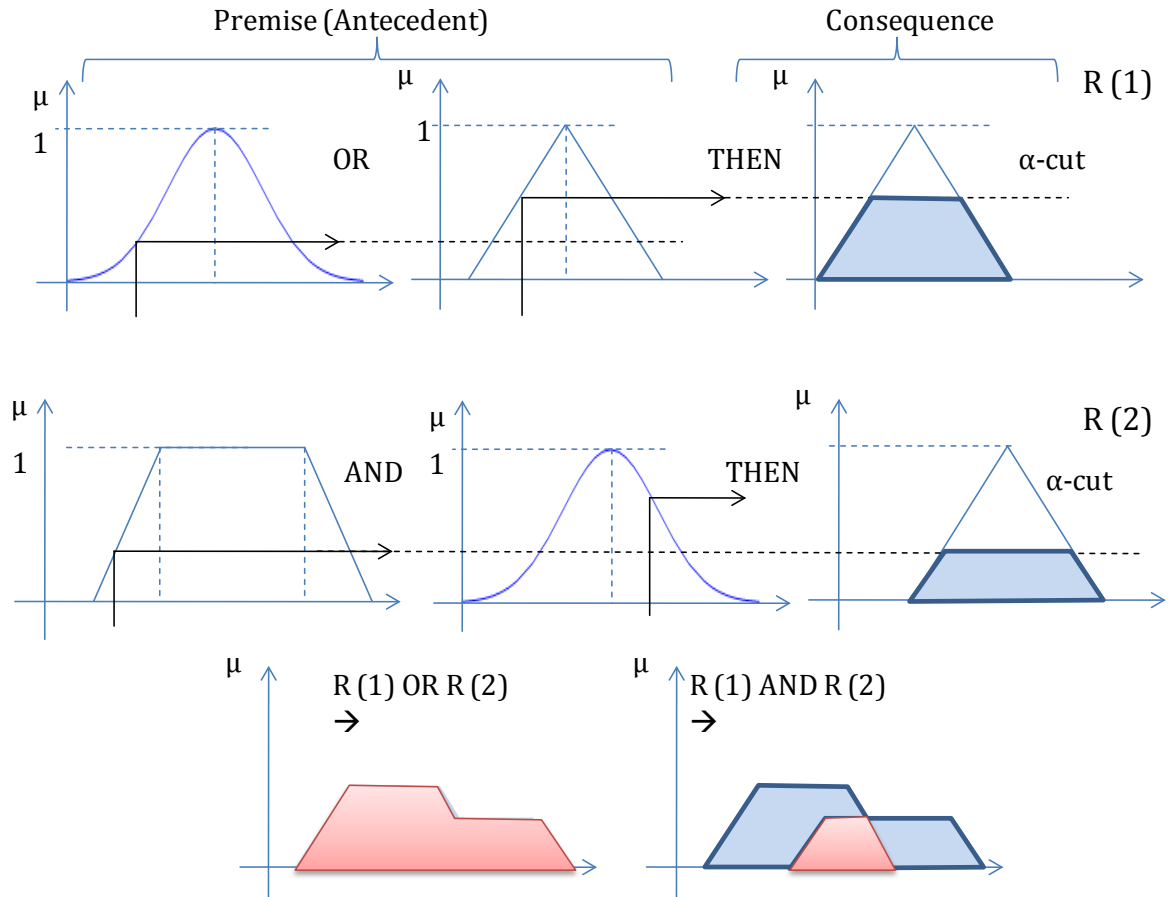


Figure 52: Mamdani fuzzy inference system (FAM) mechanism.

Moreover, it is noticeable that uncertainty subject to fuzzy systems is an intrinsic attribute of those systems with vague, ambiguous, and ill-defined conditions, which is not improvable with more observations. On the other side, uncertainty pertinent to statistical problems is distinguishable and solvable in probability theory by means of observations [270] pp 10. Thus, no exact observation leads to the fact that the problems with vagueness are not solvable with conventional probability theory.

Practically, it can be said that fuzzy inference systems are developed to competently control those systems with imprecise, uncertain and ambiguous information [175].

In summary, fuzzy (inference) systems by encompassing fuzzy logic and fuzzy sets are complementary and extensible to standard logic. Indeed, fuzzy techniques facilitate understanding, modeling, simulating, classifying, predicting, controlling, and pattern recognizing of many systems, which are strange to classical logicians [294]. Therefore, it is correctly claimed that the fuzzy decision-making system is pertinent to the development of intelligent systems [297] pp 66.

4.2.4.1 Contribution of fuzzy systems to Lpallets

It is reflected into two sections as: direct controller and indirect planner. In other words, fuzzy systems with their vast applications in engineering branches can have a great contribution to practical problems. For the last few years, the ambition for realizing the

paradigm of autonomous control system in production and logistics processes has been intensively increased. Similarly, investigation for competent methods and strategies to introduce this paradigm in its best manner has been expanded as well. However, one of the most appropriate methods is fuzzy logic.

Accordingly, this great method can be used in two formats of fuzzy inference systems and the pure fuzzy logic. It means, from planning point of view, between tactical and operational planning, fuzzy logic can be applied to reflect the flexibility and freedom of real-time controllers. In this regard, real-time controllers play a crucial role, so that they get the ability to make their own real-time tradeoffs in order to compensate dynamics happening to short term planning and scheduling activities.

In other words, fuzzy sets instead of crisp numbers get included into mathematical programming (optimization) in strategic, tactical, and, to some extent, operational planning levels. This embeds the required flexibility for real-time controllers in operational level, besides it conveys the existing practical vagueness into static and offline planning procedure. Since conventional mathematical programming is unable to meet real-time changes or disruptions in production/logistics operations, insertion of fuzzy sets in their optimization model gives rise to freedoms in the frontiers of operations. Similarly, this freedom makes real-time autonomous system to make their own decisions over real-time conditions, while they keep fuzzy schedules coming from optimization level in one step higher level.

On the other hand, imaging the autonomous objects, or in this case Lpallets, as frontier players in logistics, each gets an embedded fuzzy controller, so that the ambiguous situation in shop-floor and operational level can be perceived and controlled in a proper manner. It is quite obvious that in operational level by complex and correlated interactions between decentralized operations decentralized controllers are unable to get complete information about the entire situation of a production/logistics system. So, the information to each player is incomplete and subject to fuzzy logic with vague conditions. In contrast, a central controller for such systems may fail to control the entire system on time because of the huge complexity accompanied with correlated interactions and time delays in comprehending local changes and their effects on the global performances. It is noticeable that this context holds true for relatively massive and complex shop-floors with abundant customized operations.

Moreover, the respective FAM inside each Lpallet makes that enable to render real-time decisions based on its adapted (learned) sets in premise and consequence, objectives, and current fuzzy inputs. This improves the performance of production and logistics operations by some reasonable degrees as is experienced in corresponding experiments for the current work. More information is given in the experiments chapter related to Lpallets by the use of fuzzy system.

4.2.5 Artificial Neural Networks

Neural network (NN) is one of the most outstanding techniques in AI that is inspired by the performance of the human brain. After the great breakthrough in IT, computational operations entered into a new age in terms of capacity, speed, and precision. This revolution gave rise to a new aspiration in doing researches in the field of AI and, in particular, ANN. Today, ANN have a broad range of applications in aerospace, engineering, transportation, banking, defense affair, entertainment, medicine, etc. Accordingly, the performance of a network pertinent to ANN can be thought as a network consisting of a topology of neurons which together approximate a function to continuously map inputs to specific outputs.

Generally, two major eras are considered in the development of ANN; some of the initiative studies in ANN techniques were done at the end of 19th and the beginning of the 20th century. Some basic theories, concerning learning, looking, and conditioning, were introduced there. Later, other scientists, like Donald Hebb, continued the investigations with presenting some mathematical models inspired by the mechanisms of learning in biological neurons, see Figure 53. There the capability of ANN in computing mathematical or logical functions has been distinguished and reinforced.

In an organic neuron cell, dendrites are responsible for receiving the electrical signals from synapse of the other neurons and transmit them to the body of the cell. The cell body collects the signals and implements a threshold to them, and then when the signals reach the specific threshold the body releases a signal to other neurons via its Axon. This process was imitated by McCulloch and Pitts to design the first artificial neuron [309]. Accordingly, the power of synapse in receiving signals and the layout of neurons in a network configure the function of an NN.

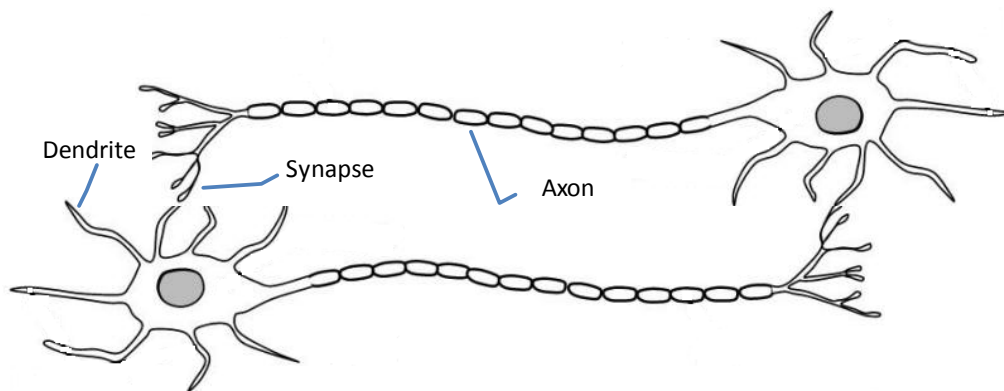


Figure 53: Two neuron in communication via Synapse and Dendrite.

In the late 1950s Rosenblatt [310] [311] and other researchers initiated the perceptron networks with their training rules. The neurons in such networks were similar to that McCulloch and Pitts already developed. Besides, it was verified that perceptrons have the ability of pattern recognition. Later, the continuous researches over NN resulted in new types of networks with different specifications for various applications. Generally, there are two significances in an NN that have been driving further developments in the field of

NN as “architecture” and “training rules” (learning algorithms). Following some facts about the both significances are given.

In fact, two or more neurons can be combined within a layer and, in addition, a network may encompass one or several such layers. The architecture of ANN is configured by the topology of neurons inside networks with regard to the number of neurons in a layer and number of layers itself. Moreover, a simple architecture of a neuron is depicted in Figure 54, in which two key elements as weight (w) and transfer function (f) play crucial roles in defining a neuron in ANN. Here, the bias (b) shifts the output of transfer function to right or left, and it is used for more precision in each neuron.

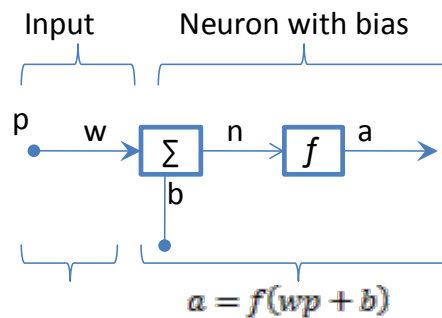


Figure 54: A simple exemplary neuron with bias from a perceptron network.

In this simple neuron the input vector p is multiplied by the weight w and is added to the bias b to result in the output (a) through the transfer function f .

However, there are several transfer (activation) functions in the form of linear and nonlinear, which return different values from similar inputs. Some famous transfer functions are: hard limit, pureline, sigmoid, radial basis, triangular basis, see Figure 55.

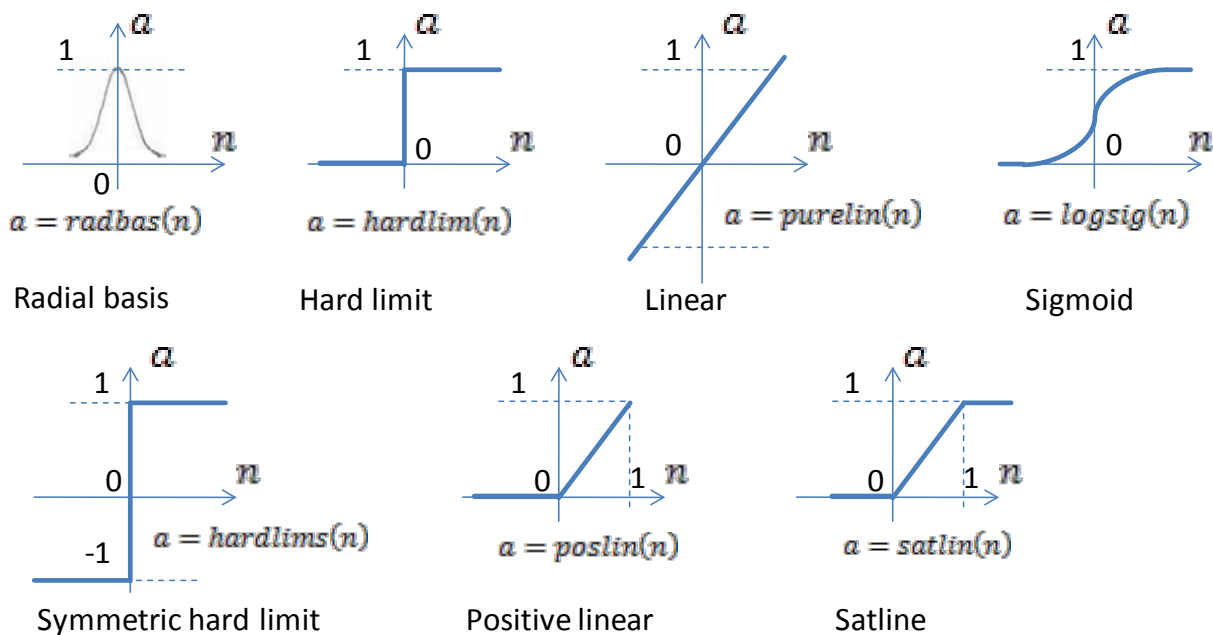


Figure 55: Some popular transfer functions.

The combination of weights, biases, transfer functions, and arithmetic operations, i.e., product, summation, in parallel neurons configures a layer in an NN. Figure 55 displays a generic format of ANN with simple multilayer topology. This network has three layers as input, hidden, and output. In layer of this type of network, an input vector \mathbf{p} is multiplied (dot product) by a weights matrix and then the bias vector \mathbf{b} is added to the product to configure the vector \mathbf{n} as the input of transfer functions in that layer. Then the transfer functions map the vector \mathbf{n} onto output vector \mathbf{a} . This procedure holds true for most networks but not for all. In the first layer of this network, R is the number of inputs, S^1 is the number of neurons in this layer and S^2 is the number of neurons in second layer. However, each layer of a multilayer ANN by itself can be a single-layer ANN. For example, the second layer of the network in Figure 56 has S^1 inputs, S^2 neurons, and \mathbf{W}^2 weights matrix with the dimension of $S^2 \times S^1$. Therefore, the number of outputs is always equal to the number of neurons in output layer.

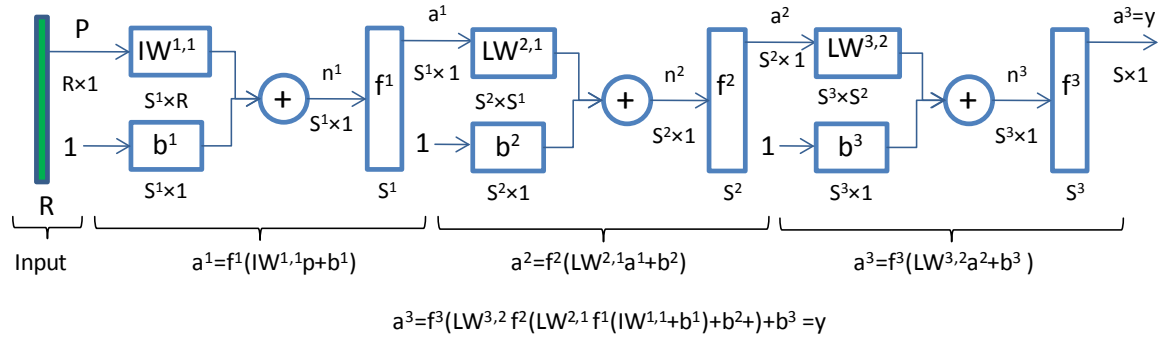


Figure 56: A simple multilayer perceptron network.

Generally, there are two main variants in networks' structures as feed-forward and recurrent. The feed-forward networks have commonly simpler topology and training rules, thus they are more popular. On the other hand, recurrent networks have more power in modeling temporal behaviors, since they use feedbacks from outputs to inputs. For example, *perceptron networks* are very famous feed-forward structured networks and Hopfield networks are pure recurrent structured, while Hamming (competitive) networks are hybrid networks combined from feed-forward layer and recurrent one.

Perceptron networks are simple feed-forward ANN that may have single-layer or multilayer structure. Single-layer perceptron networks are suitable for linear data classification, since the used transfer functions in perceptrons are usually linear. Nevertheless, *multilayer perceptrons* (MLP), by combining several linear functions in some layers, can be applied for classification of any nonlinear data as well as for approximation of any functions by combining linear and nonlinear transfer functions in layers. Each neuron in a layer has the ability to (linearly) split the input space (vectors) up into two sections, thus, more neurons in a layer further segments in the input space can be realized. Accordingly, MLP facilitate complex and nonlinear divisions in the space, since the outputs of the first layer are the inputs of the second layer with probably different transfer functions and neuron numbers, and this goes forth in other layers.

Hamming networks are hybrid networks with feed-forward and recurrent layers in their structure. This type of networks is specifically designed to distinguish binary patterns. In standard Hamming networks with two layers, the number of neurons in the first layer is always equal to the number of second layer's neurons, see Figure 56. Indeed, the goal in Hamming networks is to approximate an input vector to a sample (prototype) pattern, recorded in the recurrent layer. In other words, the goal is to distinguish the type of an input vector by approximating that to one sample pattern, so that only one neuron has nonzero output at the end. For each sample pattern in Hamming networks, one neuron exists in the recurrent layer, also called competitive layer.

In the standard network, the feed-forward layer uses linear transfer functions with bias, while transfer functions in the recurrent layer are positive transfer functions as posline² [312]. However, in doing so, the input vector and the sample patterns, as the rows of the weight matrix in feed-forward layer, produce a dot product which is summed up by bias vector. It is noticeable that if two vectors with similar norms have the same direct, then their dot product returns the maximum value and if they are perpendicular the value is minimum. The performance procedure of Hamming networks is following [313].

In fact, the output of the first layer from linear transfer functions defines the correlation degree between the input vector and sample patterns. The neuron with the highest output value in feed-forward layer has the most similarity to that sample pattern with the least Hamming distance³ from that. This distance can be only described by a binary vector though. The output of feed-forward layer is always equal to (2.2.35).

$$\text{output of feed - forward} = 2(\text{number of rows in input vector}) - 2(\text{Hamming distance from initial patterns}) \quad (2.2.35)$$

Moreover, neurons in the recurrent layer get the initial values from the outputs of the feed-forward layer and then get updated within a recurrent process to approximate the input values to an initial pattern, by following a competition and wining procedure between neurons. This is why the recurrent layer is called competition layer as well. At the end of the competition procedure just one neuron returns a nonzero value which defines the dependency of the input to a specific pattern. The competition procedure uses the following formulas within a recurrent cycle till the convergence of the network (when two consecutive outputs are similar).

$$a^2(0) = a^1 \quad (2.2.36)$$

$$a^2(t + 1) = \text{poslin}(W^2 a^2(t)) \quad (2.2.37)$$

² Is a linear function for positive values and zero for negative ones.

³ Hemming distance between two vectors is equal to the number of entities which are dislike in both vectors.

$$W^2 = \begin{bmatrix} 1 & -\varepsilon \\ -\varepsilon & 1 \end{bmatrix} \quad (2.2.38)$$

$$\varepsilon < \frac{1}{(S-1)} \quad (2.2.39)$$

where a^1 is the output of the first layer, $a^2(t)$ is the output of the second layer at time t , W^2 denotes the weight matrix in second layer. Also S stands for the number of neurons in the recurrent layer. Please note that the upper indices are the layers' number in the network.

Hopfield networks are originally recurrent networks with feedbacks. The procedure of such networks follows the procedure of the second layer in Hamming networks, as described above. However, the initial values for the neurons are directly achieved from input vector, and then the recurrent procedure (2.2.40) (2.2.41) starts till exactly one sample pattern returns in the output.

$$a(0) = p \quad (2.2.40)$$

$$a(t + 1) = \text{satlins}(Wa(t) + b) \quad (2.2.41)$$

In summary, perceptron networks with hard-limit transfer function return 0 and 1 for two clusters, in Hamming networks the neuron with a nonzero value defines the respective pattern corresponding to that neuron, and in Hopfield networks the sample pattern is directly returned in the output. Moreover, ANN are well-known tools in AI by their learning abilities and adaption to new conditions. Nevertheless, learning procedure for ANN is not a trivial process, since the effective and efficient performance of ANN is dependent on their learning quality. In other words, parameters in an ANN must be adequately trained to respond properly to inputs. For instance, weights in different layers, biases of neurons, or other parameters regarding the type of functions in neurons must get adjusted for specific applications.

Generally, there are two main types of learning (training) for ANN: supervised and unsupervised rules (also reinforcement) [314]. The supervised learning algorithms can be applied to some ANN (e.g., MLP), which already have some available training data, whilst those networks which use unsupervised learning rules have no specific pattern to follow before their own real outputs. Briefly, in supervised learning the training input data and target outputs are available and then the real outputs from those inputs are compared against the targets, and then the learning rules are used to adjust the network by means of approximating the real outputs to targets. On the contrary, unsupervised rules adjust the networks just by means of inputs and real outputs; such rules are normally used for classification of limited data clusters.

However, in addition to MLP there are more feed-forward networks like “*radial basis function*” (RBF) networks, which both are supervised training network, besides, principal

component analysis (PCA) networks, and self-organizing maps (SOMs) with unsupervised training manner[315]. Among them, RBF regarding its quick trainability and its compatibility with fuzzy systems is briefly explained here.

Generally, there are several techniques for training ANN that performance learning, associative learning, and competitive learning are some of them [316]. In performance learning, which is the focal subject in this work, the parameters of networks are adjusted to optimize the performance of the network. In such general techniques two issues are important as the performance index and the solutions space for parameters toward decreasing the performance index value (toward performance optimization).

However, the real performance index is not always available and it must be approximated. In doing so, Taylor series is employed to approximate the index around an optimum point. In other words, the Taylor series evaluated the shape of performance index in the vicinity of the optimum points, which are the optimum values for network parameters.

Taylor series in matrix form for approximating the performance index $F(x)$ around the optimum value x^* in the performance learning techniques is as follows:

$$F(x) = F(x^*) + \nabla F(x)^T|_{x=x^*}(x - x^*) + \frac{1}{2}(x - x^*)^2 \nabla^2 F(x)|_{x=x^*}(x - x^*) + \dots \quad (2.2.42)$$

$$\nabla F(x) = \left[\frac{\partial}{\partial x_1} F(x), \frac{\partial}{\partial x_2} F(x), \dots, \frac{\partial}{\partial x_n} F(x) \right]^T \quad (2.2.43)$$

$$\nabla^2 F(x) = \begin{bmatrix} \frac{\partial^2}{\partial x_1^2} F(x) & \frac{\partial^2}{\partial x_1 \partial x_2} F(x) & \dots & \frac{\partial^2}{\partial x_1 \partial x_n} F(x) \\ \frac{\partial^2}{\partial x_2 \partial x_1} F(x) & \frac{\partial^2}{\partial x_2^2} F(x) & \dots & \frac{\partial^2}{\partial x_2 \partial x_n} F(x) \\ \vdots & \vdots & \dots & \vdots \\ \frac{\partial^2}{\partial x_n \partial x_1} F(x) & \frac{\partial^2}{\partial x_n \partial x_2} F(x) & \dots & \frac{\partial^2}{\partial x_n^2} F(x) \end{bmatrix} \quad (2.2.44)$$

where $F(x) = F(x_1, \dots, x_n)$, and $\nabla^2 F(x)$ is called Hessian of $F(x)$.

There are several types of optimization methods which aim to optimize the performance index by means of iterations, e.g., SD, Newton, and conjugated Gradient, for more information see [317]. Nevertheless, all of them keep the general form of (2.2.45) for optimizing the performance index $F(x)$, i.e., finding x towards minimizing $F(x) = F(x_1, \dots, x_n)$.

$$x_{i+1} = x_i + \alpha_i p_i \quad (2.2.45)$$

thus,

$$\Delta x_i = (x_{i+1} - x_i) = \alpha_i p_i \quad (2.2.46)$$

where \mathbf{p}_i is the vector to show the search direction for optimization, α_i is learning speed that defines the step intervals toward optimization process. However, these methods are different in their search direction for \mathbf{p}_i .

Additionally, using Taylor series for approximating $F(x)$ it is given:

$$F(x_{i+1}) = F(x_i + \Delta x_i) = F(x_i) + g_i^T \Delta x_i + \frac{1}{2} \Delta x_i^T A_i \Delta x_i + \dots \quad (2.2.47)$$

where $g_i = \nabla F(x)$ and A is the Hessian matrix. Therefore, SD technique by using the first derivative in Taylor series results in (2.2.48):

$$x_{i+1} = x_i - \alpha_i g_i \quad (2.2.48)$$

As it can be seen the general form of all training algorithms follows this generic technique for optimization. Furthermore, in learning algorithms introduced in this work the SD technique is applied that minimizes a type of error as the performance index, e.g., *total sum-squared error* (TSSE), *root mean square error* (RMSE), *mean square error* (MSE). The existence of Hessian matrix in Newton and conjugated gradient optimization technique burden excessive calculation to objects with low capacity memory, means Lpallets.

Moreover, the *backpropagation training algorithm* is initiated based on LMS algorithm, both use SD technique and their performance index is MSE. Indeed, the backpropagation algorithm is an extension to the LMS algorithm. The only difference between these algorithms is in their derivative calculations (regarding Taylor series). This is because LMS algorithm is for single layer networks, while backpropagation is developed for multilayer ANN. The backpropagation algorithm is explained in detail later.

4.2.6 Multilayer Perceptron and Backpropagation Learning

After the introduction of perceptron networks by Rosenblatt it was seen that such single layer networks sometime are not able to implement certain elementary functions. This problem was solved by presentation of MLP. Basically, MLP are multilayer feed-forward ANN, which have the ability to classify any data as well as to approximate any nonlinear functions by means of several layers and transfer (activation) functions. Accordingly, MLP are known as universal approximates, which have simple topology in their structures with direct weighted connections between neurons in two consecutive layers. A perceptron network with one layer is just able to classify data linearly, whereas an MLP with two layers (one hidden and one output) is able to classify convex polygons and an MLP with three layers (two hidden) is a standard type with the ability of classifying any shapes [408].

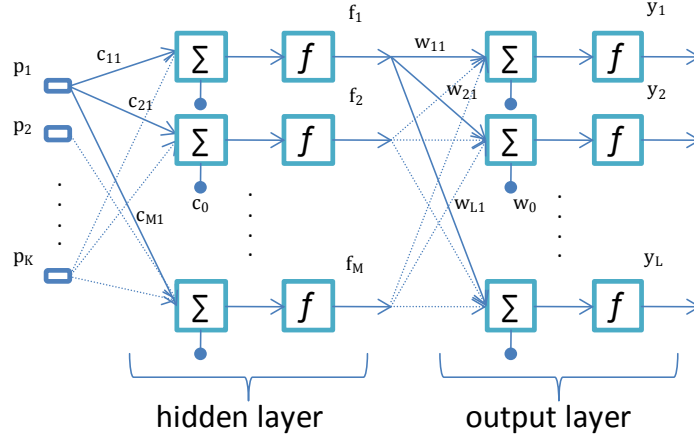


Figure 57: An exemplary MLP with two layers.

Figure 57 shows an MLP with two layers, as one hidden and one output layer. In this network, the l^{th} output can be simply calculated by (2.2.49).

$$y_l = \sum_{j=0}^M w_{lj} \Phi_j \left(\sum_{k=0}^K c_{jk} p_k \right); \quad \text{with } \Phi_0(\cdot) = 1 \text{ and } p_0 = 1 \quad (2.2.49)$$

where p_k is the k^{th} input element in the input vector, c_{jk} define the weights from input to hidden layer, Φ_j denotes the j^{th} function in the hidden layer, w_{lj} stands for j^{th} weight from hidden layer to the l^{th} output in output layer, y_l represents the l^{th} output of the network, besides, w_{0l} and c_{j0} are biases. In addition, the functions in hidden layer are usually hard limit or sigmoid [314] [408]. In addition, $\mathbf{p}_i = [p_1 \cdots p_k \cdots p_K]^T$ $\mathbf{y}_i = [y_1 \cdots y_l \cdots y_L]^T$ hold true.

Multilayer perceptrons by means of iterative gradient descent optimization routine called “*backpropagation*” training algorithm are very popular in several applications of ANN. However, this algorithm has some shortcomings that do not always guarantee the convergence in training and is slow in some cases [409]. This problem is addressed by the difficulty in determining optimal steps in iterations of the algorithm toward optimum parameters and convergence, i.e., size and direction in the weights’ space as well as initial values. However, this problem is directly dependent on the chosen optimization technique in the algorithm; if either of these problems can be solved, then training speed and/or convergence can be improved. Nevertheless, this algorithm has enough calculation simplicity to be employed by limited memory objects (like Lpallets) for real-time/online training. Thus, this has motivated its application in the current study. Following a brief introduction to the origin of the backpropagation algorithm is given.

Now, for perceptron networks there is a general training rule which is extended to develop other learning rules. Since perceptrons are supervised learning networks, this general rule operates based on the error between real outputs and target ones in the network. Below the general format of the rule is represented:

$$\mathbf{W}^{\text{new}} = \mathbf{W}^{\text{old}} + \mathbf{e} \mathbf{p}^T \quad (2.2.50)$$

$$\mathbf{e} = \mathbf{a} - \mathbf{y} \quad (2.2.51)$$

where $\mathbf{e} = [e_1 \dots e_L]^T$ is the error vector, $\mathbf{a} = [a_1 \dots a_L]^T$ denotes the target output vector, $\mathbf{p} = [p_1 \dots p_L]^T$ defines the input vector, $\mathbf{y} = [y_1 \dots y_L]^T$ denotes the real output vector, and \mathbf{W} is the weights matrix;

$$\mathbf{W} = \begin{bmatrix} w_{1,1} & \dots & w_{1K} \\ \vdots & \ddots & \vdots \\ w_{L1} & \dots & w_{LM} \end{bmatrix} \quad (2.2.52)$$

On the other hand, one of the preliminary rules for ANN learning was introduced by Donal Hebb [410] and is called *Hebb rule*. Generally, the Hebbian theory can be formulated like (2.2.53), for training parameters of ANN that is called associative learning as well.

$$w_{jk}^{new} = w_{jk}^{old} + \alpha a_{ji} p_{ki} \quad (2.2.53)$$

where $i = 1, \dots, N$ is the number of training vectors, w_{jk} is the weight which connects the input element k to output element j , a_{ji} defines the target output for j^{th} neuron in the i^{th} training input vector, p_{ki} stands for the k^{th} input element in the i^{th} training input vector. In order to control the number of members in weights' matrices in the Hebb rule the learning speed α is initiated. However, the above equation is an unsupervised rule for training. In case of supervised learning with some available training values, the practical version of Hebb rule, according to the difference between target outputs and real outputs (error), can be displayed as (2.2.54):

$$\mathbf{W}^{new} = \mathbf{W}^{old} + \alpha(\mathbf{a}_i - \mathbf{y}_i)\mathbf{p}_i^T \quad (2.2.54)$$

The above equation is called *delta rule*, *Widrow-hoff rule*, and *least mean square* (LMS) algorithm between training algorithms [411]. Indeed, this rule by adjusting the weights matrix minimizes the *mean square error* (MSE) in this equation. Moreover, if a new pattern as an input is introduced to an ANN then the delta rule can update the weights. This is the great advantage of this rule that makes it compatible with continuously adaptive environments, whereas some other rules like pseudo-inverse rule require the entire training package for their performance. Please not that in dynamic environments, like logistics, this property of delta rule is quite appealed.

However, the complete form of LMS algorithm with using MSE as performance index is following:

$$\mathbf{W}_{i+1} = \mathbf{W}_i + 2\alpha \mathbf{e}_i \mathbf{p}_i^T \quad (2.2.55)$$

However, Hebb rule has several types but most of the available algorithms for training ANN apply directly or indirectly this rule in their procedure. The backpropagation algorithm which is explained later is developed based on this rule. Additionally, the Widrow-hoff rule exploits steepest descent (SD) optimization method. Optimization

methods are to tune the performance of learning algorithms and, basically, each learning rule follows a specific optimization technique.

4.2.7 Radial Basis Function Networks

RBF networks are originated from multidimensional interpolation models and can also be classified into feed-forward networks with supervised learning feature, see Figure 58. RBF networks like MLP have popularity in their ability of approximating nonlinear functions [318] [319] besides data classification [315] [320]. In fact, an RBF network can approximate an arbitrary function by linearly combining some basis functions. The simple structure in RBF networks motivates abundant applications of such networks [321]. Nonetheless, RBF networks have some structural differences from MLP networks as follows [315]:

- Because of transfer functions in the hidden layer of RBF networks, they are recognized as local approximates, while MLP are known as global approximates. Each neuron in hidden layer of an RBF network returns a significant nonzero value just when the input falls within a small localized region of the function center (input space). Passing through each kernel function limits the response space to a local zone. But in MLP functions, like sigmoid in output layer, it gives a significant positive value within a wide range of input space.
- Number of hidden layers in MLP can be more than one, whereas RBF networks have just two layers as one hidden layer, and one output layer (three layers by considering inputs as the input layer).
- The output layer in MLP can be linear or nonlinear (e.g., sigmoid), but RBF networks have always linear functions in output layer.
- The most important difference between the two networks is in their neurons' performances. Transfer functions in hidden layer of an RBF network compute the Euclidean distance [322] between input vector and center of transfer function (usually Gaussian basis function), whilst in MLP dot product between input vector and the relevant weight vector is calculated.

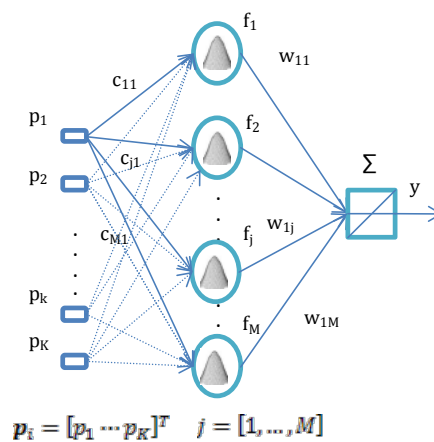


Figure 58: A simple RBF network with one-node output.

However, RBF networks have some advantages which make this type of ANN suitable for data classification as well as function approximation [319]. For instance, RBF networks have the capability of universal approximation (can approximate any smooth nonlinear function) like MLP, RBF networks have the attribute of best approximating (precise approximation, ease of training, robustness, memory complexity, or computational complexity), which MLP do not always have it. In addition, in very similar applications RBF networks have some superiority over MLP like accuracy and faster training procedure [323] [324]. Nevertheless, MLP and RBF networks have several comparable capabilities, which make the decision over their selection difficult. Thus, their learning performance on particular data sets is normally a good criterion for selecting one of them. It is noticeable that locally optimization of parameters in RBF networks [322] is a privilege over MLP to have better flexibility in decentralized and distributed problems.

Learning algorithms for RBF networks span a wide range of pure and hybrid methods. Generally speaking, learning an approximation for the correct relationship between the output and input spaces by means of estimating network parameters is called training procedure for a network [325]. Indeed, learning for RBF networks encompasses the configuration of a multidimensional surface that fits best to the training data. Generally, each RBF network has three main parameters to be learned through a training procedure; 1) number of neurons in hidden layer, 2) center and width of each basis function in a neuron, 3) the output weights, has to be defined by a training set of N input-output pairs $\{\mathbf{p}_i, y_i\}, i = 1, \dots, N$ (if the output has more than one-node then output is a vector too instead of a single value).

$$y_i = \sum_{j=1}^M w_j \cdot f_j(\|\mathbf{p}_i - \mathbf{c}_j\|) + (\varepsilon_i) \quad (2.2.56)$$

where $\|\cdot\|$ denotes Euclidean norm, $\mathbf{p}_i = [p_1 \cdots p_K]^T$ indicates the i^{th} training input vector with K -dimension, M denotes the number of neurons in hidden layer, w_j stands for the weights in output layer (coefficients of the linear combination), $f_j(\mathbf{p}_i)$ is the output of the basis function in j^{th} neuron of hidden layer, ε_i is the offset of the output to fit the model to the true input-output relation (error in each training procedure). Note that the Euclidean norm is computed for the shifting operation of input vector from center of basis function by means of Euclidean distance of both vectors, which is minimum when they are in the least distance and maximum by further distance from each other [319].

Additionally, if the basis function is Gaussian then following equation (2.2.57) holds true. Then the vector $\mathbf{c}_j = [c_{j1} \cdots c_{jK}]^T$ denotes the K -dimensional center of the Gaussian function in j^{th} neuron, which is equal to all respective input weights from K -dimensional input vector to that neuron, σ_j is scale factor (width of Gaussian function).

$$y_i = \sum_{j=1}^M w_j \cdot \exp\left(-\frac{\|\mathbf{p}_i - \mathbf{c}_j\|^2}{2\sigma_j^2}\right) + (\varepsilon_i) \quad (2.2.57)$$

In general, two ways of supervised learning can be imagined in the form of offline and online learning. However, conventional training algorithms are offline learning by means of available input and output sample (training) data to train a network. According to Khajeh *et al.* [326] training strategies for RBF networks have two main categories; those strategies that define suitable centers and variances of the trained network like, see also [315] [327]:

- Fixed centers selected at random,
- Self-organized selection of centers; *K*-means clustering procedure, the self-organizing feature map clustering procedure,
- Supervised selection of centers,
- Supervised selection of centers and variances.

The other category encompasses those strategies in which the weights of the network are distinguished and optimized, like following methods:

- The pseudo-inverse,
- The least mean square (LMS),
- The steepest descent (SD),
- The quick propagation method.

One general form of such training methods using the pseudo-inverse to achieve weights in output layer can be achieved as follows, see [325]:

$$h_j(\mathbf{p}_i) = f_j(\|\mathbf{p}_i - \mathbf{c}_j\|) \quad (2.2.58)$$

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{w} + \boldsymbol{\varepsilon} \quad (2.2.59)$$

$$\mathbf{H} = \begin{bmatrix} h_1(\mathbf{p}_1) & \cdots & h_M(\mathbf{p}_1) \\ \vdots & \ddots & \vdots \\ h_1(\mathbf{p}_N) & \cdots & h_M(\mathbf{p}_N) \end{bmatrix} \quad (2.2.60)$$

$$\hat{\mathbf{w}} = (\mathbf{H}^T \cdot \mathbf{H})^{-1} \cdot \mathbf{H}^T \cdot \mathbf{y} = \mathbf{H}^+ \cdot \mathbf{y} \quad (2.2.61)$$

where \mathbf{H} denotes the design matrix of the network and \mathbf{H}^+ is its pseudo-inverse $\mathbf{w} = [w_1 \ w_2 \ \cdots \ w_M]^T$ stands for the weights vector and $\hat{\mathbf{w}}$ is its approximation, $\mathbf{y} = [y_1 \ y_2 \ \cdots \ y_N]^T$ represent the vector of outputs for N training inputs, $\boldsymbol{\varepsilon} = [\varepsilon_1 \ \varepsilon_2 \ \cdots \ \varepsilon_N]^T$ is the error vector. Moreover, $\hat{\mathbf{w}}$ is approximated by means of MSE, using \mathbf{H}^+ by pseudo-inverse rule [328]. However, other parameters like M , \mathbf{c}_j , and σ_j must be either available (e.g., randomly chosen) or estimation of them are due to a complex algorithms like combined one with regression tree [329], which is computationally complex enough to be implemented by Lpallets. Furthermore, this method for offline learning requires the complete training vector of input-output, which is not always available with regard to the current study.

However, other training algorithms for RBF networks include: support vector machines, relevance vector machines, orthogonal least squares algorithms, recursive least square based algorithms, generalized growing and pruning [330], the backpropagation algorithm [331] [332], non-symmetric partition of input space [333]. Among them just backpropagation as a variant of the gradient descent algorithm, due to its simplicity and online application capability [331], is selected to be used for Lpallets in the current study. Here, the online capability means the ability of updating parameters of the training network immediately after each input-output training pair. In particular, the specific backpropagation algorithm with best selective training (BST) developed by Vakil-Baghmisheh *et al.* [332], because of its calculation simplicity and capability in quick updating parameters is adopted and briefly explained below. Besides, there the pattern mode training with single data, which is appropriate for online training with step-by-step optimization, is advantageous, since in batch mode training all data must be available.

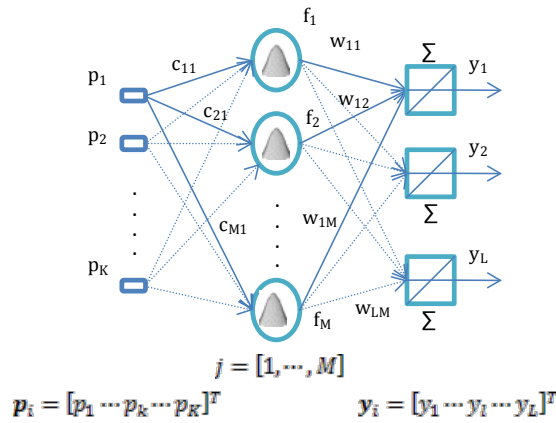


Figure 59: An RBF network with multi-outputs.

Moreover, in their work three common types of functions, which are used to map outputs of the hidden layer to outputs of the network, are considered as sigmoid, linear with $\frac{1}{M}$ squashing function, and pseudo-linear, with $\frac{1}{\sum_j f_j}$ squashing function:

$$y_l = \begin{cases} \frac{1}{1+e^{-s_l}}; & \text{sigmoid (1)} \\ \frac{s_l}{M}; & \text{linear (2)} \\ \frac{s_l}{\sum_j f_j}; & \text{pseudo-linear (3)} \end{cases} \quad (2.2.62)$$

where $j = [1, \dots, M]$ is the number of neurons in hidden layer, $y_i = [y_1 \dots y_2 \dots y_L]$ is the i^{th} output vector which defines L number of neurons in output layer.

$$s_l = \sum_{j=1}^M f_j w_{lj} ; l = 1, \dots, L \quad (2.2.63)$$

Furthermore, always a cost function (performance index) must be defined for training; there are some types of error evaluations, as mentioned before, which are popular in different training algorithms. Nonetheless, only TSSE, because of its easy derivative, is used

for following training algorithm. Now, assuming the RBF network in Figure 59, the normal backpropagation algorithm updates the parameters of the network by the following equations (2.2.64), (2.2.65), (2.2.66):

$$w_{lj}(t+1) = w_{lj}(t) - \alpha_3 \frac{\partial E}{\partial w_{lj}} \quad (2.2.64)$$

$$c_{jk}(t+1) = c_{jk}(t) - \alpha_2 \frac{\partial E}{\partial c_{jk}} \quad (2.2.65)$$

$$\sigma_j^2(t+1) = \sigma_j^2(t) - \alpha_1 \frac{\partial E}{\partial \sigma_j^2} \quad (2.2.66)$$

where $\alpha_1, \alpha_2, \alpha_3$ are the learning speed, which are less than 1 (i.e., the maximum learning value $\alpha < 2/\lambda_{\max}$ that λ_{\max} is the biggest eigenvalue of Hessian matrix), t stands for event (epoch) which new input vector is introduced, w_{lj} represent coefficient weights in output (from hidden layer), c_{jk} denotes weights from inputs to hidden layer, σ_j^2 stands for variance/scale factor of j^{th} hidden neuron, and E represents error.

$$\frac{\partial E}{\partial w_{lj}} = \begin{cases} \left[(-2(a_l - y_l)) \frac{f_j}{M} \right]; & \text{in case (1)} \\ \left[(-2(a_l - y_l)) \frac{f_j}{\sum_{j=1}^M f_j} \right]; & \text{in case (2)} \\ \left[(-2(a_l - y_l)) y_l (1 - y_l) f_j \right]; & \text{in case (3)} \end{cases} \quad (2.2.67)$$

where a_l is the target (training) output in l^{th} output neuron, y_l denoted real output from neuron l in output layer, f_j stands for output of the j^{th} basis function (neuron) in hidden layer.

$$\frac{\partial E}{\partial c_{jk}} = \begin{cases} \sum_{l=1}^L (-2(a_l - y_l)) \frac{w_{lj}}{M} \frac{f_j}{\sigma_j^2} (p_{jk} - c_{jk}); & \text{in case (1)} \\ \sum_{l=1}^L (-2(a_l - y_l)) \frac{w_{lj} \sum_{o=1}^M f_o - s_l}{(\sum_{o=1}^M f_o)^2} \frac{f_j}{\sigma_j^2} (p_{jk} - c_{jk}); & \text{in case (2)} \\ \sum_{l=1}^L (-2(a_l - y_l)) y_l (1 - y_l) w_{lj} \frac{f_j}{\sigma_j^2} (p_{jk} - c_{jk}); & \text{in case (3)} \end{cases} \quad (2.2.68)$$

$$\frac{\partial E}{\partial \sigma_j^2} = \begin{cases} \sum_{l=1}^L (-2(a_l - y_l)) \frac{w_{lj}}{M} f_j \left(\frac{\|\mathbf{p} - \mathbf{c}_j\|^2}{2\sigma_j^4} \right); & \text{in case (1)} \\ \sum_{l=1}^L (-2(a_l - y_l)) \frac{w_{lj} \sum_{o=1}^M f_o - s_l}{(\sum_{o=1}^M f_o)^2} f_j \left(\frac{\|\mathbf{p} - \mathbf{c}_j\|^2}{2\sigma_j^4} \right); & \text{in case (2)} \\ \sum_{l=1}^L (-2(a_l - y_l)) y_l (1 - y_l) w_{lj} f_j \left(\frac{\|\mathbf{p} - \mathbf{c}_j\|^2}{2\sigma_j^4} \right); & \text{in case (3)} \end{cases} \quad (2.2.69)$$

where \mathbf{p} denotes the input vector and \mathbf{c}_j is the center vector for j^{th} neuron.

- Half training: Only the weight matrix of the output layer was under training.
- Half training: The weight matrix of the output layer and kernel vectors were under training.
- Full training: The weight matrix of the output layer, kernel vectors and spread parameters were under training.

Despite good learning algorithms, sometimes the results are not satisfactory this is mostly because of ill-defined initial values for parameters in such networks. Therefore, well defining initial values are important as well. However, this issue is dependent on the type of input data and application of the network. They may be chosen randomly in some cases (if no initial perception exists for inputs), randomly chosen from sample data (if some available), they can be derived from first sample data, or using a specific algorithm like k -means or learning vector quantization (LVQ) [332]. For instance, for scale (spread) factor in hidden layer (2.2.70) holds true.

$$\sigma = \frac{d}{\sqrt{2M}} \quad (2.2.70)$$

where d defines the maximum distance between centers of functions (in hidden layer). Or logically the standard deviation of vectors in a subclass can be chosen as σ . Additionally, for weights in output layer they may be randomly chosen from the range of $[-0.1 \ 0.1]$ with learning for improvement, or by means pseudo-inverse algorithm calculating the respective pseudo-inverse matrix from available training data, which is not always the case in Lpallets. Besides the calculation complexity of achieving the pseudo-inverse matrix hinders the algorithm in this specific application.

Furthermore, the notion of selective training proposed by Vakil-Baghmisheh *et al.* is quite useful in case of intermittently emergence of new patterns after an adequate degree of learning. In doing so, they suggest selectively using inputs, and not all, for training after the specific epoch that TSSE gets smaller than a threshold. However, the distinction of this threshold and the selective inputs is subjective and an empirical procedure. For instance, the threshold in the current study for Lpallets can be distinguished by simulation experiments as well as the stability proportion in a certain period. Nonetheless, there, the selective procedure via online training can automatically be accomplished through increasing the number of neurons in the hidden layer by a new out of range pattern.

Here, each new input— introduced to the built network of an Lpallet— is fed forward to the network. Now, if its domain is already met by the current network, then no training happens to that input. Otherwise, if the input value falls behind the existing ranges, then either a new neuron is added to the network topology, the current network undergoes a new training iteration, or both alternatives happen simultaneously.

Moreover, application of RBF network for Lpallets has some specifications, which are unique in this study. Indeed, employment of dynamic structure for respective RBF networks in Lpallets— in addition to the competency of online learning— gives rise to flexibility in RBF networks to adapt to dynamic circumstances given in logistics operations. There, the number of neurons changes by the stepwise learning method, through accomplishment of each cyclic operation. Accordingly, when a new pattern in the learning phase is recognized this is reflected in the network by embedding a new basis neuron, while the extinct patterns are removed by aborting corresponding neurons. This is talked later in more details in the section pertinent to Lpallets and experiments.

4.2.7.1 Contribution of ANN to Lpallets

It is realized for each Lpallet as intelligent controller and decision-maker. Each Lpallet is provided by a neural network for accepting the values of predefined metrics and rendering decisions based on them. For instance, in an assembly line Lpallets can take the waiting and processing time of stations and configure (train) their networks in order to make decisions over the sequence of operations in a closed-loop system. However, this procedure is deeply explained in the experiments' chapter in the sections relevant to RBF networks for Lpallets. Furthermore, ANN can be employed centrally to make decisions over routing, inventory control, and demand forecast in SN, which is not covered in the current work.

4.3 Simulation

Simulation is a competent approach to reduce the costs of unsuitable strategic decisions, planning, and performances of a system. It assists improvement of virtual models before implementing them in the real world. In other words, simulation is a model of a real thing to be used for learning, sensitivity analysis, or solving complex problems with have no straightforward solutions. According to Bisschop [334] pp 7, a modeling process can be divided into five steps as follows.

- Defining the goal of the model
- Consulting experts and collecting information
- Formulating the model
- Running the initial test of the model
- Validating that by known input/output data

Generally, simulation is defined as a prominent tool in doing experiments before practical implementations with efficiency [335]. Indeed, simulation is a virtual model of a system's behaviors with the capability to experiment with different scenarios and making sensitivity

analysis. However, two major classes of simulation are continuous time (e.g., Vensim) and discrete-event time (e.g., Plant-Simulation). The Plant-simulation package is developed by SIMENSE for the purpose of simulating production and logistics scenarios with the capability of programming different policies and scenarios. In the current work, this package is thoroughly employed to prove theories and suggested concepts.

Moreover, a measurement approach has to be accompanied with modeling of a system to evaluate the success of key performance indicators (KPI), i.e., KPI show the performance of the system. These have to be evaluated by simulation. Some underlying KPIs in a supply chain are cost, cycle time, lead time, completion time, inventory & stock level, customer satisfaction, and delivery reliability. According to Zagonel *et al.* [336] testing a model in practice has to pass some control aspects, among them are:

- Boundary adequacy test
- Structure assessment test
- Dimensional consistency
- Parameter assessment
- Extreme conditions test
- Behavior reproduction
- Sensitivity analysis
- System improvement test

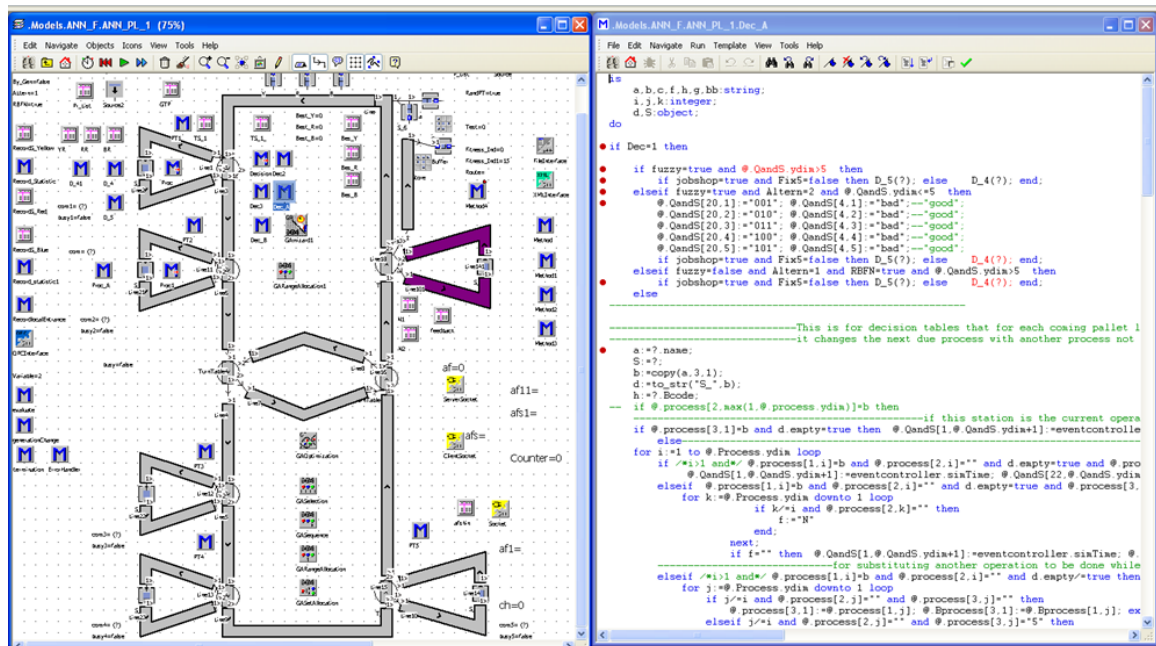


Figure 60: Exemplary simulation model of a car light assembly line located at BIBA institute, modeled by Plant-simulation.

In summary, simulation is thoroughly used in the current work as the main tool for modeling, experimenting, justifying, and testing different logistics' scenarios with alternative methodologies, e.g., autonomous objects, conventional flow control.

4.4 Mathematical Programming/Optimization

This section complies with mathematical programming as the general methodology for studying, modeling, solving, and optimizing those optimization problems with cost functions as objectives and some linear or non-linear constraints. However, the purpose of this section is just a brief introduction to this method in order to underscore the role of fuzzy programming in delimiting the required freedoms in static mathematical programming at tactical level. This embedded freedom leads to the realization of the autonomous logistic objects in dynamic environments, while keeping conventional and integrated plans throughout SN. It is noticeable that the scope of this study is not to widely cover the contribution of mathematical programming by means of fuzzy to the output of this work as specific logistic objects (Lpallets).

Generally, an optimization model is a mathematical prototype of a problem which is intended to be optimally solved according to one or more objective(s) and some constraints if any. This type of mathematical model is an abstract model that is called mathematical programming in general [334] pp 14. Basically, optimization of a problem refers to achievement of maximum degree of satisfaction with doing the least amount of effort for solving the problem [278] pp 1. Initially, the optimization algorithm deals with efficiency and effectiveness factors in achieving the optimum degree of satisfaction [337].

Mathematical programming is the core of any organizing framework packages, like ERP and APS [67] pp 3. The use of mathematical programming gives rise to integration and optimization of processes throughout any organization spanning from SN to small shop-floors. The tasks of strategic and production planning, inventory management, transportation, as well as scheduling, all can be modeled by mathematical programming either solely or in an integrated form to optimize their objectives. The models must be optimized in such a way that all constraints get satisfied. However, it is not always straightforward to find optimum values for objectives, since production and logistics parties in SN have usually different and heterogeneous targets. Therefore, several alternatives have been developed to hold tradeoffs between such objectives.

In general, several types of mathematical programming with optimization purpose exist that the major classes of them are as below [334] [338] pp 5:

- Linear programming (LP): refers to those minimization/optimization problems with linear objective(s) and linear equality and inequality constraints. Additionally, all variables are continuous,
- Mixed integer programming (MIP): refers to optimization of linear objective function(s) with linear constraints like LP, while some variables accept integer values,
- Constraint programming (CP): refers to optimization problems to solve a system of constraints with alternative forms according to a set of indefinite discrete variables probably with an objective of minimization/maximization,

- Nonlinear programming (NLP): refers to those problems with either nonlinear objective(s) or constraints or both over unspecified real variables,
- Mixed integer nonlinear programming (MINLP): refers to problems with nonlinear characteristics as well as containing integer variables,
- Stochastic programming (SP): contrary to the other programming types, this optimization problem refers to those of them that take into account uncertainty of input parameters with a set of states.
- Robust optimization (RO): contrary to the other programming types, this optimization problem refers to those of them that take into account uncertainty of input parameters with uncertain ranges, e.g., fuzzy numbers, see [339].

However, modeling the planning and scheduling problems in logistics and production networks by mathematical programming is not equivalent to solve them accordingly. The existence of contradictory goals for each party of such complex interactive networks necessitates heuristic solutions for solving the models. Nevertheless, the planning and scheduling of material flow operations is central to organizing operations. Thus, mathematical programming is conventionally deployed to all sections of SN.

On the other hand, mathematical programming models are subject to be solved by static solvers. In other words, as Persson *et al.* [136] say, optimization models reflect SC at a definite occasion of time without considering dynamic aspects, e.g., in opposite to simulation. Basically, mathematical programming performs over optimization of one or more objective function(s) according to some constraints that bound the solution space of the respective optimization problem. Now, if some of constraints are not available at a moment, the solution space may be infeasible to get solved.

In fact, in addition to the modeling optimization problem by means of mathematical programming, the notion of optimization refers to finding the best solution between several available alternatives (maybe over a time horizon) to find the global optimum. Moreover, available solvers for mathematical programming are central oriented solvers with accepting parameters of the problem as inputs and map outputs based on constraints. Complexity in mathematical programming models and respectively in their solvers makes them inappropriate tools for real-time decisions by means of local perceptions and under highly dynamic circumstances. Indeed, these specifications of mathematical programming contradict that from real-time decision makings, which is inherent to autonomous objects.

However, by proposing fuzzy robust mathematical programming the respective mathematical model can become subjective and decision maker gets the possibility to reflect his/her preferences in the model [339]. Thereby, the objective of this work becomes closer to the reality. It was already explained in the motivation section that confrontation with dynamics in logistics poses two aspects as: adaptation to dynamics as well as adoption of dynamic behaviors into own performances. In other words, the suggested framework for application of autonomous logistic processes depicts two implementation approaches from top-down as well as bottom-up. The top-down approach considers the

conventional APS into account, and then by an extension to that proposes the required tolerance (freedom/uncertainty) for autonomous objects in the parameters and variables of the mathematical programming embedded in APS. In doing so, fuzzy robust optimization and stochastic programming can be applied solely or in a hybrid form. This leads to incorporation of the limited freedom caused by decentralized and distributed decision makings in real-time by autonomous logistic objects to static mathematical programming for tactical and operational levels. On the other hand, the autonomous objects, as the frontier players at operational level, acknowledge the given limited freedom to them and perform by their own decisions on local control problems, while committing to the given production planning and scheduling fuzzy set outputs.

Moreover, it is already discussed before that the operations in manufacturing and logistics environment exposed to dynamics and complexity, besides human intervention, resemble fuzzy nature. Indeed, fuzzy nature holds true rather than stochastic nature; because in a distributed environment, ill-defined information and lack of all required data for making a decision in real-time is inevitable [285] pp 6, [340].

However, application of fuzzy set theory in mathematical programming leads to several advantages. Among which are by setting satisfaction degree for multi-objective problems it becomes possible to normalize the problem and convert them into a single objective problem with maximization of satisfaction degrees for every single objective. This case is broadly discussed by Sakawa in his book [285]. In addition, by means of fuzzy sets it is possible to define robust dimensions for fuzzy constraints with fuzzy parameters and make a robust optimization model, according to Zhang *et al.* [339].

Generally, a linear mathematical model is defined as:

$$\text{Min } z = CX \quad (2.4.1)$$

s.t:

$$AX \leq B \quad (2.4.2)$$

$$X \geq 0 \quad (2.4.3)$$

where $A \in \{R\}^{n \times m}$, $B \in \{R\}^{n \times 1}$, $C \in \{R\}^{1 \times m}$, $X \in \{R\}^{n \times 1}$, R denotes a set of real number, n and m denote integer values for row and columns of matrix $\{R\}^{n \times m}$.

According to Zimmermann *et al.* [341] and Shih *et al.* [342], fuzzy mathematical programming can be generally classified into the problems with fuzzy objective, with fuzzy constraints, and both. Now, if the coefficients in constraints instead of crisp values belong to fuzzy sets, i.e., $A \in \{\mathfrak{R}\}^{n \times m}$, $B \in \{\mathfrak{R}\}^{n \times 1}$, with \mathfrak{R} as a set of fuzzy parameters, then the mathematical programming problem gets into fuzzy space domain with nonconventional solution methods. Thus, one way to solve such problems is the use of fuzzy robust programming, so that the difficulties accompanied with fuzzy numbers both on the left-

and right-hand side, see [339]. In this manner, the constraints of the fuzzy problem can be converted into deterministic constraints by means of delimitation. In fact, this delimitation represents the required tolerance between inferior and superior values in fuzzy set, suitable for imprecision in consequent autonomous decisions. Then the fuzzy robust linear programming can be rewritten as follows, see [339]:

$$\text{Min } z = CX \quad (2.4.4)$$

s.t:

$$\sum_{j=1}^m (\bar{a}_{ij}^p x_j) \leq \bar{b}_i^p; \quad i = 1, \dots, n; p = 1, \dots, k \quad (2.4.5)$$

$$\sum_{j=1}^m (\underline{a}_{ij}^p x_j) \geq \underline{b}_i^p; \quad i = 1, \dots, n; p = 1, \dots, k \quad (2.4.6)$$

$$x_j \geq 0; \quad j = 1, 2, \dots, n \quad (2.4.7)$$

where $\bar{t} = \sup(t)$, $\underline{t} = \inf(t)$, \sup denotes supremum and \inf stands for infimum of sets, and k represents k levels of α -cut [342] [343] [344].

Moreover, considering the work of Zimmermann *et al.* [341], mathematical programming may have fuzzy conditions over the objective and constraints, in a generic form, see also [340]. In this manner, the problem can be formulated as follows:

$$CX \lesseqgtr z_0 \quad (2.4.8)$$

$$AX \lesseqgtr B \quad (2.4.9)$$

$$X \lesseqgtr 0 \quad (2.4.10)$$

where \lesseqgtr is a symbol of relaxed or fuzzy version of conventional inequality, and z_0 is called aspiration level of decision maker to define its target for the problem. Then by substituting following notations:

$$\begin{pmatrix} C \\ A \end{pmatrix} = D \quad (2.4.11)$$

$$\begin{pmatrix} z_0 \\ B \end{pmatrix} = \hat{B} \quad (2.4.12)$$

Then the linear membership function of i^{th} fuzzy constraint $(DX)_i \lesseqgtr \hat{B}_i$ is interpreted like below, see Figure 61:

$$\mu_i((DX)_i) = \begin{cases} 1 ; & (DX)_i \lesseqgtr \hat{B}_i \\ 1 - \frac{(DX)_i - \hat{B}_i}{o_i} ; & \hat{B}_i \lesseqgtr (DX)_i \lesseqgtr \hat{B}_i + o_i \\ 0 ; & (DX)_i \geq \hat{B}_i + o_i \end{cases} \quad (2.4.13)$$

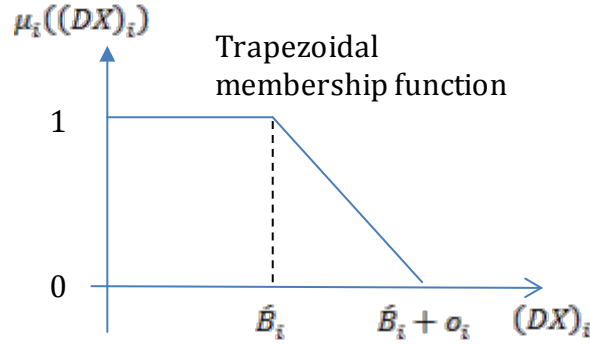


Figure 61: Linear membership function for i^{th} fuzzy constraint.

Now, according to the extension principle of Zadeh [345] [346] pp 14, the mathematical programming can be changed to the maximization of membership function as the purpose of decision maker, see following.

$$\max \min_{0 \leq i \leq n+1} \mu_i((DX)_i) \quad (2.4.14)$$

s.t:

$$X \geq 0 \quad (2.4.15)$$

Thus, according to Zimmerman [347] [348], by means the transformation variable $B_i'' = \frac{\hat{B}_i}{o_i}$, $(\acute{D}X)_i = (DX)_i/o_i$, and auxiliary variable $\lambda = \min_{0 \leq i \leq n+1} \mu_i((DX)_i)$ the problem is transferred into conventional linear programming like below, this methods is called min operator too.

$$\max \lambda \quad (2.4.16)$$

s.t:

$$\lambda \leq 1 + B_i'' - (\acute{D}X)_i ; i = 0, \dots, n+1 \quad (2.4.17)$$

$$X \geq 0 \quad (2.4.18)$$

Another, possibility for fuzzy mathematical programming is to have fuzzy parameters in both objective and constrains. This situation can be shown as follows, see Sakawa *et al.* [346]:

$$\text{Min } z = \tilde{C}X \quad (2.4.19)$$

s.t:

$$\tilde{A}X \leq \tilde{B} \quad (2.4.20)$$

$$X \geq 0 \quad (2.4.21)$$

where $\tilde{A}, \tilde{B}, \tilde{C}$ are matrices with fuzzy parameters as $\tilde{A} = [\tilde{a}_{ij}]; i = 1, \dots, n; j = 1, \dots, m$, and $\tilde{B} = [\tilde{b}_i]; i = 1, \dots, n$ and $\tilde{C} = [\tilde{c}_j]; j = 1, \dots, m$.

To solve this problem, one competent solution in literature is α -cut based model, see also Shih *et al.* [342]. In doing so, for a certain degree α , defined by decision maker, the ordinary set of $(a, b, c)_\alpha$, with membership degrees over α , can be written as:

$$(a, b, c)_\alpha = \left\{ (A, B, C) \mid \mu_{\tilde{c}_j} \geq \alpha, \mu_{\tilde{a}_{ij}} \geq \alpha, \mu_{\tilde{b}_i} \geq \alpha, i = 1, \dots, n, j = 1, \dots, m \right\} \quad (2.4.22)$$

So, for the sake of simplicity, the problem is changed to non-fuzzy and can be again rewritten as follows:

$$\left. \begin{array}{l} \text{Min } c_1x_1 + \dots + c_mx_m \\ \text{s. t:} \\ a_{11}x_1 + \dots + a_{1m}x_m \leq b_1 \\ \dots \dots \\ a_{n1}x_1 + \dots + a_{nm}x_m \leq b_n \\ x_j \geq 0, j = 1, \dots, m \\ (A, B, C) \in (a, b, c)_\alpha. \end{array} \right\} \quad (2.4.23)$$

Here, the parameters (A, B, C) are changed to decision variables in α -linear programming problem. Furthermore, the α -cut level defines feasible intervals for each fuzzy number \tilde{a}_{ij} , \tilde{b}_i , and \tilde{c}_j , so as left L and right R boundaries $[\tilde{a}_{ij\alpha}^L, \tilde{a}_{ij\alpha}^R]$, $[\tilde{b}_{i\alpha}^L, \tilde{b}_{i\alpha}^R]$, and $[\tilde{c}_{j\alpha}^L, \tilde{c}_{j\alpha}^R]$. Conclusively, the problem leads into several conventional linear programming with alternative α -cut levels.

$$\left. \begin{array}{l} \text{Min } c_1^Lx_1 + \dots + c_m^Lx_m \\ \text{s. t:} \\ a_{11}^Lx_1 + \dots + a_{1n}^Lx_m \leq b_1^R \\ \dots \dots \\ a_{n1}^Lx_1 + \dots + a_{nm}^Lx_m \leq b_m^R \\ x_j \geq 0, j = 1, \dots, m. \end{array} \right\} \quad (2.4.24)$$

It is noticeable that each fuzzy number may have its own membership function, for more information see section pertinent to fuzzy set theory. In additional, similarly, the level-cut (α -cut) method can be used to nonlinear programming, for more information see Shih *et al.* [342].

Furthermore, multi-objective programming (MOP) facilitates decision-making with multiple contradictory objectives by means of compromising between alternatives [339]. Moreover, by converting the multi-objective functions into a deterministic problem by means of the fuzzy programming method and min operator, it becomes possible to integrate decision maker satisfaction degree with effectively handling uncertainties between objectives (or constraints) in MOP. One way to convert MOP into a single objective problem is to simply define a satisfaction degree for each of the objective and then according to the extension principle maximizing the minimum of membership degrees in each objective. As mentioned this is broadly explored by Sakawa [285] and used by Petrovic *et al.* [298] and Fayad *et al.* [349]. For example, if we have two contradictory objectives in a MOP with one maximization and one minimization objective, then the decision maker should define the intervals and membership functions of each objective. In fact, each of these membership functions corresponding to an objective is interpreted as satisfaction degree; so the task is to uniformly maximize the minimum of satisfaction degrees, like following:

$$\text{Max } \min(\mu_{\tilde{a}}, \mu_{\tilde{b}}, \mu_{\tilde{c}}) \quad (2.4.25)$$

$$\text{s.t.} \quad \mu_{\tilde{a}} = \begin{cases} 1 & ; \quad \text{if } x_1 \leq h_1 \\ \frac{q_1 - x_1}{q_1 - h_1} & ; \quad \text{if } h_1 \leq x_1 \leq q_1 \\ 0 & ; \quad \text{if } q_1 \leq x_1 \end{cases} \quad (2.4.26)$$

$$\mu_{\tilde{b}} = \begin{cases} 1 & ; \quad \text{if } q_2 \leq x_2 \\ \frac{x_2 - h_2}{q_2 - h_2} & ; \quad \text{if } h_2 \leq x_2 \leq q_2 \\ 0 & ; \quad \text{if } x_2 \geq q_2 \end{cases} \quad (2.4.27)$$

$$\mu_{\tilde{c}} = \begin{cases} 1 & ; \quad \text{if } x_1 \leq h_3 \\ \frac{q_3 - x_1}{q_3 - h_3} & ; \quad \text{if } h_3 \leq x_1 \leq q_3 \\ 0 & ; \quad \text{if } q_3 \leq x_1 \end{cases} \quad (2.4.28)$$

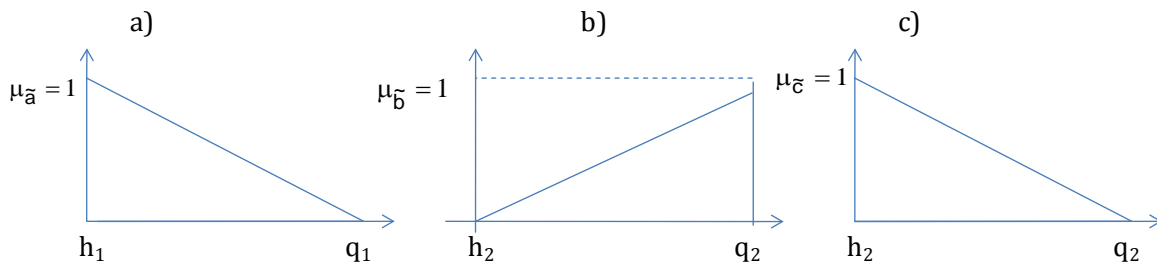


Figure 62: a) and c) the membership functions of minimization and b) the membership function of maximization objective.

where x_1 , x_2 , and x_3 can have any function or value. It is noticeable that each of the objectives may have some specific interaction with other objectives that can be taken into

account as well. This approach for MOP is the simplest technique for aggregating multi-objectives in a unique satisfaction degree. Here, the aggregation operator is chosen as *min* of membership degrees (which is the most commonly used and simpler operator between others), for more information see, Sakawa [285] pp 58. However, the boundaries for objectives (i.e., h and q), concerning their satisfaction degrees, have to be subjectively selected by decision maker, see Figure 62.

Thus, after the brief explanation about fuzzy mathematical programming and cover small aspects of that, this contribution can be directly used by conventional mathematical programming embedded in APS.

4.5 Queuing Theory

Queuing theory is a branch of probability theory that emerged 100 years ago, also known as traffic theory, congestion theory, theory of mass service, and theory of stochastic service systems [350] pp 16. Basically, queuing theory is a mathematical theory for modeling, designing, and quantitatively analyzing (the length of service and waiting times in) any system with servers, and clients. In other words, it is an analysis tool for studying the relationships between congestion and delay by defining derivation of characteristic quantities such as TP and waiting time, in those of systems with servers and buffers and some jobs to be processed, e.g., communication systems, banking systems, production systems. Additionally, by means of this theory's analysis predicting the future behavior of queuing systems and optimizing them besides understanding their dynamics is possible. Some further practical examples of queuing theory are: response times in telephone exchanges and process computers, buffer dimensioning, TP in wireless networks or assembly lines, and waiting time for each station in production lines. The results of queuing analysis can be directly applied in scheduling problems. It is noticeable that this section is generally written based the lecture note of Professor Görg for Communication Networks II [351].

Generally, a queuing system can be recognized by three important characteristics: the input process, the service mechanism, and the queue discipline. The input process is often described by the probability distribution of the length of time between consecutive customers' arrival instants. This is because arrivals are mostly the product of external factors. Thus, the arrival process is described by random variables to represent either the number of arrivals in a time interval or the time interval between two consecutive arrivals (inter-arrival time). The service mechanism consists of the number of servers and the durations of service time for customers and mode of service. The most uncertain value in this mechanism is the service time that often is represented by a random variable too. The queue discipline defines the disposition of those customers face busy servers (blocked customers). Generally, blocked customers either leave the system or wait in a queue for service. Accordingly, the discipline expresses the rule, based on which a server accepts customers, waiting in the queue for service [352]. Nonetheless, there are several disciplines in queues for treating waiting customers, see Figure 63.

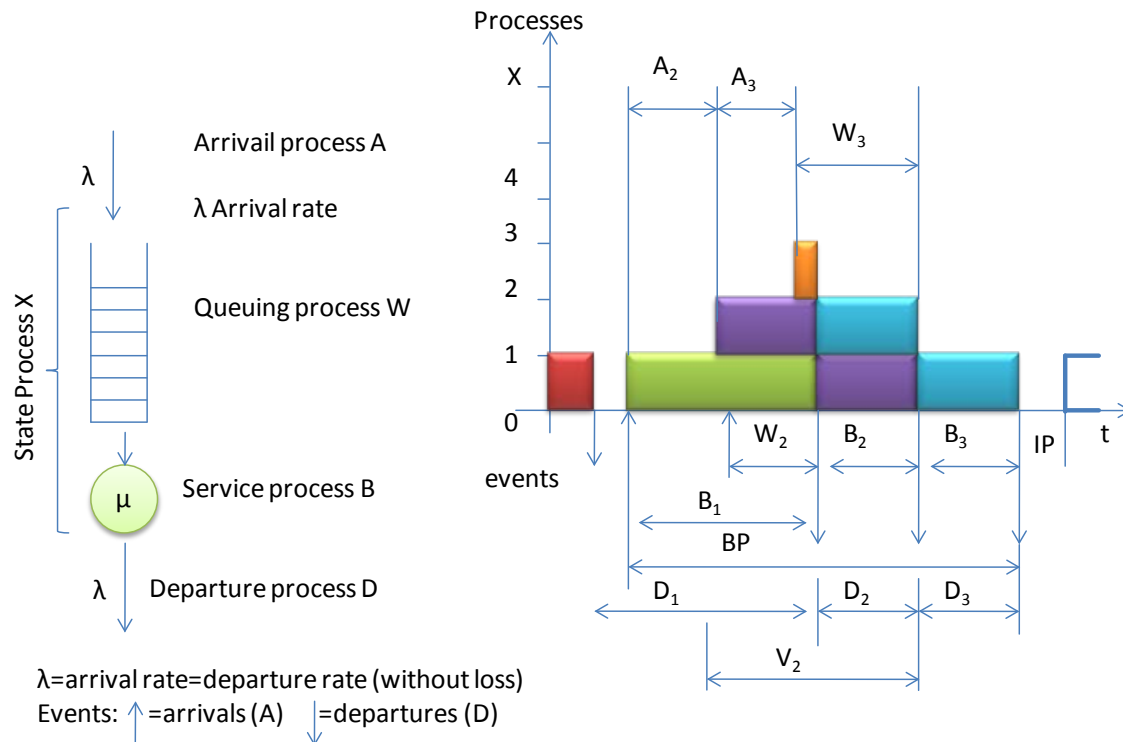


Figure 63: Details of processes in a queuing system in terms of waiting, processing, and departure times, adopted from [351].

However, the attributes of queuing systems are usually represented by A/S/n/d/e symbols, known as Kendall classification, to denote queuing models. Here several symbols in literature are combined together, and the general format is achieved as below:

A/S/n/c-d/e/f

- A= arrival process, e.g., distributions of Markovian (M), Deterministic (D), Erlang-k.
- S= service process, e.g., distributions of Markovian (M), Deterministic (D), Erlang-k.
- n= number of servers.
- c= max size of the waiting line/ queue capacity (if ∞ omitted).
- d= queuing discipline/scheduling strategy for queue, e.g., First-Come-First-Serve (FCFS/FIFO), Last-Come-First-Serve (LCFS/LIFO), Serve-In-Random-Order (SIRO), Priority queue, round robin (RR), Shortest-Processing-Time (SPT), if FIFO or not specified can be omitted.
- e= scheduling strategy corresponding to external priorities between the queues (if relevant, otherwise blank).
- f= number of possible customers, for open systems omitted.

Furthermore, each of the symbols in the taxonomy of queuing systems can undertake a variety of possibilities. For instance, M/M/1 represents the arrival and service processes as Markov with one server, and M/G/3/20 shows Poisson arrival, three servers with the general distribution (any distribution), maximum number of 20 customers. Following the important sections of this symbol as arrival and service processes (in detail) as well as queuing discipline, and scheduling strategy related to external priorities (briefly) are explained:

4.5.1 Arrival and Service Process

For the inter-arrival and service times of arrival and service process, they may accept different distributions, and correspondingly probability mass function (pmf) for discrete or probability density function (pdf) for continuous random variables. Actually, inter-arrival times or service times are usually continuous random variables unless the processes are considered in discrete-time. In fact, discrete random variable in an arrival process is the number of arrivals during a time T .

Initially, queuing systems are based on stochastic processes; thereby, queuing theory has shown its fertility in fundamentally studying stochastic processes involving mathematical models. "Queues are special case of stochastic processes that are identified by a state $X(t)$ denoting the number of queued entities" [412] pp 306. A stochastic process is defined by several distributions of random variable X at alternative time events t . In fact, a random variable assigns a value to each output s in a sample space S , while a stochastic or random process arranges a sample function $x(t, s)$ to each outcome s .

Generally, a stochastic process is characterized by following, for more information see [412] p 306:

- State of the stochastic process at time t , state $X(t)=x$
- State space, the set of possible values that $X(t)$ can include. The space may be continuous or discrete (then the stochastic process is called chain)
- Time variable t that can be owned by a continuous or discrete set
- Correlation characteristics between $X(t)$ random variables at different instant t values.

Whereas in stochastic process there may be a correlation dependency on time between two random variables, the random variables in distribution function are independent.

The probability density function (pdf) of random variable X for all instants $t=\{t_1, t_2, \dots, t_n\}$ and values of $x=\{x_1, x_2, \dots, x_n\}$ for any n is described by (13):

$$PDF_x(x, t) = Prob\{X(t_1) \leq x_1, X(t_2) \leq x_2, \dots, X(t_n) \leq x_n, \} \quad (2.5.1)$$

The common processes and their distributions for arrival and service are as follows:

- M= Markovian process/ negative exponential distribution
- D= Deterministic distribution
- E_k = Erlang-k distribution
- GE= General Erlang distribution
- H_r = r^{th} order hyper-exponential distribution
- G= General distribution

Markovian process/ negative exponential distribution (M) represents negative exponential distribution (neg-exp) for continuous and geometric distribution for discrete-

time in the respective process. This type of distribution is derived from Markovian process and is often used to approximate the distribution of inter-arrival and service times. While the inter-arrival time follows neg-exp, the number of arrivals within an interval follows Poisson distribution (2.5.3). The simplicity of this process regarding its memory-less property makes it abundant in approximating queuing processes. Commonly, in manufacturing systems the arrival process can be approximated by negative exponential distribution (Poisson process) [413].

$$P(T = t) = (1 - p)^{t-1}p \quad (2.5.2)$$

$$P(T \leq t) = 1 - e^{-\lambda t} \quad (2.5.3)$$

where p is the probability of success. For illustrating the feature of Markov process it has to be explained as follows. It is a special case of stochastic process whose specific characteristic is such that probability distribution for its future development depends only on its present state and not on its trajectory in the past. (2.5.4) is the definition of Markov process that signifies its memorylessness:

$$P[X_{t_{n+1}} = x_{n+1} | X_{t_n} = x_n, X_{t_{n-1}} = x_{n-1}, \dots, X_{t_1} = x_1] = P[X_{t_{n+1}} = x_{n+1} | X_{t_n} = x_n]; \forall n = 1, 2, \dots; t_m \in I; \text{for any real } x_n \quad (2.5.4)$$

Thus, the cumulative density function (cdf) of a random variable x_{n+1} is determined for any pair of $t_{n+1}, t_{n+1} \in I$ via the conditional cdf:

$$F(t_n, x_n, t_{n+1}, x_{n+1}) = P[X_{t_{n+1}} = x_{n+1} | X_{t_n} = x_n] \quad (2.5.5)$$

Markov chain is a special case of Markov process with discrete state space and time. Accordingly, the set of stochastic variables $\{X_1, X_2, \dots, X_n\}$ is called Markov chain if for all n (steps) and all positions of i and j the following equation (2.5.6) holds true.

$$P[X_{n+1} = j | X_1 = i_1, X_2 = i_2, \dots, X_n = i_n] = P[X_{n+1} = j | X_n = i] = P_{ij} \quad (2.5.6)$$

$p_{ij}(t_1, t_2)$ is the transition probability $i \rightarrow j$ which gives the conditional probability, that X_t with the present value of i at time t_1 ($X_{t_1} = i$) takes the value j at time t_2 ($X_{t_2} = j$).

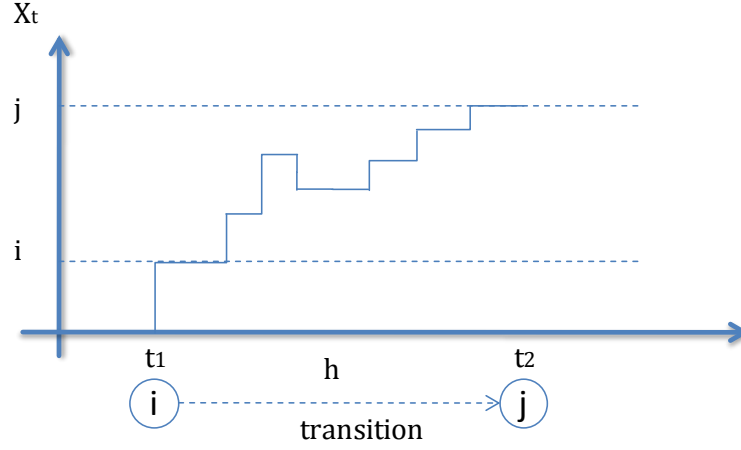


Figure 64: The transition of $i \rightarrow j$ from t_1 to t_2 .

Stochastic (routing) matrix of transition probabilities (1...n states) is following:

$$p_{ij}(t_1, t_2) = p_{ij}(t_2 - t_1) = p_{ij}(h) \quad (2.5.7)$$

$$P(h) = \begin{bmatrix} p_{11}(h) & \cdots & p_{1n}(h) \\ \vdots & \ddots & \vdots \\ p_{n1}(h) & \cdots & p_{nn}(h) \end{bmatrix} \quad (2.5.8)$$

$$\sum_{j=1}^n p_{ij}(h) = 1, h \geq 0, \text{ for all } i \quad (2.5.9)$$

However, statistical equilibrium has a crucial role in analyzing stochastic systems. This specification reflects the equality of entrance rate to a state and departure rate from a state. These equations hold true in the stationary state of Markov process (2.5.14).

$$P[X_{t+h} = i] = P[X_t = i] = p_i \quad (2.5.10)$$

$$q_{kj} = \lim_{t \rightarrow 0} \frac{p_{kj}(t)}{t}; k \neq j \quad (2.5.11)$$

$$q_j = \lim_{t \rightarrow 0} \frac{1 - p_{jj}(t)}{t} \quad (2.5.12)$$

$$q_j = \sum_{k \neq j} q_{jk} \quad (2.5.13)$$

$$q_j p_j = \sum_{k \neq j} q_{kj} p_k \quad (2.5.14)$$

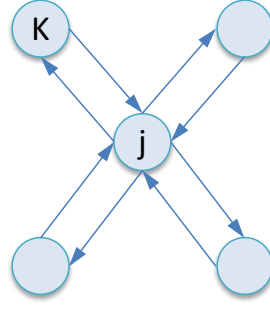


Figure 65: Statistical equilibrium of state transition.

where q_j is the rate to leave state j (from j), p_j is the state probability to be in state j , q_{kj} is the transition rate from state k to neighboring state j . For more information about the properties of Markov chains and their states see [414] pp 29, [412] pp 305, [415] pp 24.

Therefore, based on Chapman-Kolmogorov equation in a homogenous process (2.5.15) holds true for two steps of transition:

$$p_{ij}^{(s+\hat{s})} = \sum_{k \neq j} p_{ik}^{(s)} p_{kj}^{(\hat{s})}, \quad \text{if } p_{ik}^{(m)} > 0 \quad (2.5.15)$$

where m is step transition with probability p_{ij} . Moreover, homogenous means the transition of probability is independent of the step.

A well-known example of Markov process is the special process of birth and death (BD). Within BD process transitions occur only to direct neighbors. $\{A_t\}$ counts all the arrivals and $\{D_t\}$ counts all the departures up to the time instance t . $\{N_t\} = \{A_t\} - \{D_t\}$ is a homogenous stationary BD process with transition probabilities $p_{ij}(h)$. The state transition diagram of one dimensional BD process is depicted in Figure 66. Here, the transition rate can be calculated by (2.5.16):

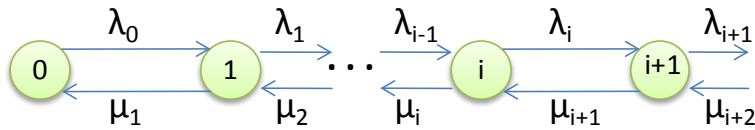


Figure 66: State transition diagram of the BD process.

$$q_{ij} = \begin{cases} \lambda_i & j = i + 1, i = 0, 1, \dots \text{ "birth rate" } \\ \mu_i & j = i - 1, i = 1, 2, \dots \text{ "death rate" } \\ 0 & \text{otherwise} \end{cases} \quad (2.5.16)$$

where the interpretation of λ in queuing systems is the arrival rate and μ is the service rate. Then according to the statistical equilibrium the state equilibrium of neighboring state in BD process is as (2.5.17):

$$\lambda_{i-1} p_{i-1} = \mu_i p_i \quad (2.5.17)$$

The best instance for BD process is the Poisson process as a pure BD process [352], pp 229. A special case of counting process is called Poisson process with λ parameter if probability of the number of events $P_i(t)$ in the time interval t follows Poisson distribution (2.5.18):

$$P_i(t) = \frac{(\lambda t)^i}{i!} e^{-\lambda t}, \quad i = 0, 1, \dots, t \geq 0 \quad (2.5.18)$$

The difference in equations between the Poisson process and Poisson distribution is in time t . If the equation uses λt this is the process and if just λ is used this represent the distribution, since there is a direct relation between Poisson process and neg-exponential distribution with memoryless property.

However, the state transition diagram can be depicted when the system is in discrete-time domain. For instance, M/M/ i describes a station with i servers with Markovian arrival $\lambda = \lambda_i ; \forall i \in I$ and service process. Then in this case from the $i + 1$ state, queue is built up and this holds true $\mu_i = \mu_{i+1} = \mu_{i+2} = \dots$. Here, the notations like λ is the arrival rate that follows Poisson distribution, $\mu = n\varepsilon$ stands for the general service rate of a station, ε is the service rate of one server in the station, and $\beta = \frac{1}{\varepsilon}$ denotes the mean service time for one server $n = 1$.

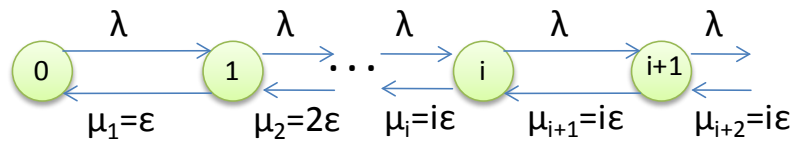


Figure 67: Finite state process as special BD process.

Generally, there are some key performance indicators (KPI) for evaluating the performance of queuing systems [353] [416]. For all KPI it is assumed that system is in a steady state situation.

- The “state probability” p_n (2.5.19) is the probability of existing n customers in the queuing system (being served or waiting),

$$\pi_n = p_n = Pr\{n \text{ customers in system}\} \quad (2.5.19)$$

- The “system load” or “traffic intensity” ρ (2.5.20), which is given by the ratio of offered traffic and number of servers, arrival rate over service rate, or the ratio of average service time β and average of inter-arrival time $t = \frac{1}{\lambda}$,

$$\rho = \frac{A}{n} = \frac{\lambda}{n\varepsilon} = \frac{\lambda}{\mu} \quad (2.5.20)$$

Here, if $\rho > 1$ then the system is unstable and the capacity of that is less than required. This way increases the queue length to infinity over the time. If $\rho < 1$ the system is stable in steady state condition and if $\rho = 1$ then there exist no queue.

- The “departure rate” or “throughput” (2.5.21) that is the average number of customers leaving the system. In the steady state situation departure rate and arrival rate are equal.

$$TP = \sum_{n=1}^{\infty} \mu_n p_n \quad (2.5.21)$$

- The “average time in system” V and the “average queuing time” or “average waiting time in queue” W_q , describe the time a customer has to wait in the system and in the queue until service starts, respectively ,

$$V = W_q + \frac{1}{\mu} \quad (2.5.22)$$

- The “average number of customers in the system” or “average system size” L in steady state (2.5.23),

$$L = \lim_{t \rightarrow \infty} E(P(t)) = \sum_{n=1}^{\infty} n p_n \quad (2.5.23)$$

- The “average queue length/size” L_q (2.5.24) denotes the mean number of customers in the queue,

$$L_q = \lambda W_q \quad (2.5.24)$$

The very last equation for defining the relation between the mean number of customers in the queue and mean waiting time of them was initially determined by J.D.C. Little, which is known as “Little’s Law”. The arrival rate multiplying by mean waiting time in the queue gives the mean queue size (2.5.24). Correspondingly, (2.5.25) holds true as well.

$$L = \lambda V \quad (2.5.25)$$

The Little’s Law is a general key for solving and analyzing queuing systems, since it is not specified for any particular arrival or service distributions, queuing discipline, or number of servers. In addition, when the system is in a steady state situation the following equations can be used (fully for single server in each station).

$$p_0 = \pi_0 = 1 - \rho \quad (2.5.26)$$

$$p_n = \pi_n = \rho^n (1 - \rho) \quad (2.5.27)$$

$$L = \frac{\rho}{1 - \rho} = \frac{\lambda}{\mu - \lambda} \quad (2.5.28)$$

$$L_q = \frac{\rho^2}{1 - \rho} = \frac{\lambda^2}{\mu(\mu - \lambda)} \quad (2.5.29)$$

$$V = \frac{1}{\mu - \lambda} \quad (2.5.30)$$

$$W_q = \frac{\lambda}{\mu(\mu - \lambda)} \quad (2.5.31)$$

For other famous distributions in queuing systems see [417]. As mentioned, several practical systems exist, which can be modeled by means of queuing networks, e.g., job-shops, large computers, department stores. Commonly, queuing networks are interconnected service stations that each of them provides specific service and are decoupled through buffers [418], pp 57.

4.5.2 Open Queuing Network

Open queuing networks are those with changing number jobs with entering and departure, see Figure 68. There are two variants for open networks with feed forward and feedback structure. In former one a job cannot visit a queue more than once, whilst in feedback networks jobs may appear more than once in the same queue. Some assumptions are considered for open queuing networks as below:

- The open network is in a steady state (no transient state)
- Each station may encompass one or more servers
- Some individual transition probabilities can be zero

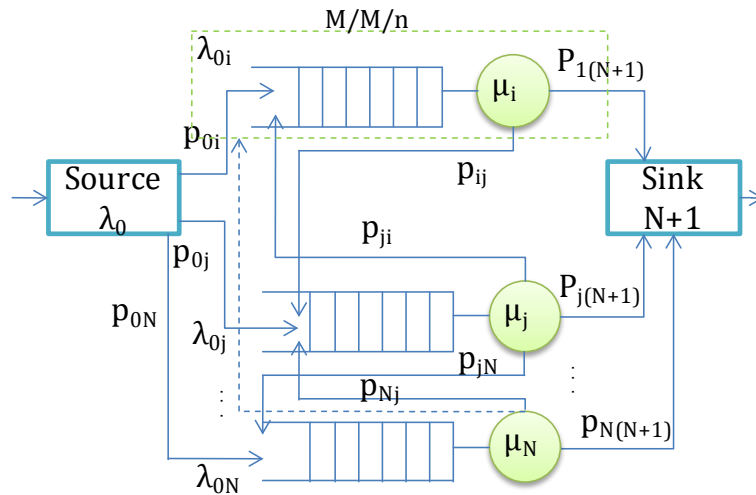


Figure 68: Exemplary of a general open queuing network.

The used notations for open networks are following (Table 6):

Table 6: Used notations for open networks.

| Notation | Description |
|-----------------------------------|--|
| ε_i | Service rate of one server in station i |
| n_i | Number of servers in station i |
| $\mu_i = n_i \cdot \varepsilon_i$ | Service rate in (one) station i |
| p_{ij} | Transition probability from station i to station j |

| | |
|--|--|
| $\lambda_i = \lambda_0 + \sum_{j=1}^N p_{ji} \lambda_j$ | Total arrival rate (TP) at station i |
| $1 - \sum_{j=1}^N p_{ij}$ | Probability $p_{i(N+1)}$ for leaving the network after station i |
| $\lambda_{0i} = p_{0i} \cdot \lambda_0$ | Arrival rate from source to station i ; $\lambda = \lambda_0$ |
| $\underline{k} = k_1, k_2, \dots, k_N$ | State (vector) of the system with N stations |
| k_i ; $i = 1, 2, \dots, N$ | Number of jobs at station i |
| $P(\underline{k})$ | State probability |
| $p_i(k_i)$ | Boundary probability for having exactly k_i jobs in station i |
| $e_i = \frac{\lambda_i}{\lambda} = p_{0i} + \sum_{j=1}^N e_j p_{ji}$ | Relative frequency of visits to station i |
| V | Total mean response time of the network (sojourn time) |

However, a famous theorem for analyzing open queuing networks is Jackson's theorem, see [353] pp 46. Briefly saying, Jackson's theorem holds true for open and closed networks in case of some assumptions:

- in a network with N stations all stations must have neg-exponential (M-distribution) for service time and follow FCFS strategy, and the arrival process is Poisson, i.e., M/M/n for each station,
- just a unique class of jobs exists,
- there is no limited capacity for queues
- no overload happens to stations $\lambda_i < \varepsilon_i \cdot n_i$
- then the state probability can be calculated in product form (2.5.32)

$$P(\underline{k}) = \prod_{i=1}^N p_i(k_i) ; i = 1, 2, \dots, N ; k_i = 0, 1, \dots, \infty \quad (2.5.32)$$

Accordingly, the following equations can be derived.

$$p_i(k_i) = \begin{cases} p_i(0) \frac{(n_i \rho_i)^{k_i}}{k_i!} & \text{if } k_i \leq n_i \\ p_i(0) \frac{n_i^{n_i} \rho_i^{k_i}}{n_i!} & \text{if } k_i \geq n_i \end{cases} \quad (2.5.33)$$

$$L_i = n_i \rho_i + L_{qi} \quad (2.5.34)$$

$$L_{qi}(n_i = 1) = \frac{\rho_i^2}{1 - \rho_i} \quad (2.5.35)$$

$$L_i = \frac{\rho_i}{1 - \rho_i} ; n_i = 1 \quad (2.5.36)$$

$$V_i = \frac{L_i}{\lambda_i} = \frac{\rho_i}{\lambda_i(1 - \rho_i)} \quad (2.5.37)$$

$$V = \frac{1}{\lambda} \sum_{i=1}^N L_i = \frac{1}{\lambda} \sum_{i=1}^N \frac{\rho_i}{(1-\rho_i)} \quad (2.5.38)$$

$$\lambda = \sum_{i=1}^N \lambda_{0i} \quad (2.5.39)$$

4.5.3 Closed Queuing Network

The other variant of queuing networks is closed queuing networks with rich application in practice. When a short circuit happens to the source and the sink of an open system/network then this system/network resembles a closed system/network, see Figure 69. The main feature here is that the k -number of jobs circulating within a closed network is always constant, thus, the buffers do not need any capacity more than k . Closed networks facilitate easier mapping of multiple independent resources, in order utilization of resources by the jobs, concurrent application of alternative resources by unlike jobs [351].

In closed networks the assumptions of Jackson's theorem works as well, just small modifications have to be done to those in open networks, like:

$$\sum_{i=1}^N k_i = K \quad (2.5.40)$$

$$\lambda_i = \sum_{j=1}^N p_{ji} \lambda_j \quad (2.5.41)$$

$$e_i = \sum_{j=1}^N e_j p_{ji} \quad (2.5.42)$$

Logically, the number of different states n_s In closed networks is identical to the number of possibilities to distribute K jobs between N stations. This can be derived by the combination (2.5.43).

$$n_s = \binom{N+K-1}{N-1} \quad (2.5.43)$$

However, practical operations in different systems like production systems do not only include manufacturing of homogenous products, but a variety of them by the same production lines. Thus, the introduction of alternative jobs in queuing networks gives rise to a better analysis of such systems by means of queuing theory. For this purpose, generally, jobs in queuing networks can be clustered into job classes/chains. The classification of jobs distinguishes between jobs with different behaviors, and types, e.g., specific processing. Job classes can be used for both open and closed networks, so that via classification even hybrid form of open-closed networks can be realized. In this manner, some job classes can arrive at and departure from the network, whilst some other classes circulate within the network. Correspondingly, for each class a stochastic routing matrix (matrix of transition probability) must be developed to illustrate the transition probabilities of specific class of jobs in their routings.

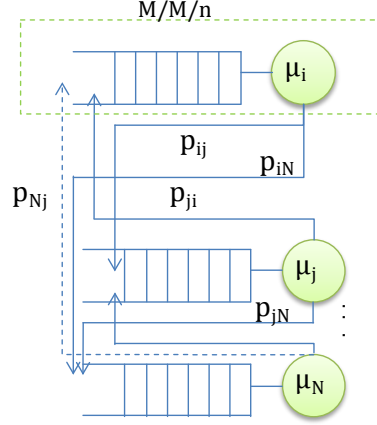


Figure 69: An exemplary closed queueing network.

In addition to the Buzen's algorithm [354] for calculating normalization constant in solving queueing networks with common jobs, Baskett, Chandy, Muntz and Palacios (BCMP) model was introduced for those closed networks with different classes of jobs. BCMP model assumes any finite number of stations N , finite number of job classes R , arbitrary service time distributions, and the change in class of job is possible with probability of $p_{i,r;j,s}$. Table 7 shows the specific notations used in the BCMP model for closed networks.

Table 7: Used notations in BCMP model for closed networks.

| Notation | Description |
|--|--|
| $p_{i,r;j,s}$ | Probability that a class r job after receiving its service at station i changes to class s and requires service at station j |
| $\underline{P} = [p_{i,r;j,s}]$ | Matrix of transition probability, defining a Markov chain with states |
| E_m | Ergodic (irreducible) sub-chains of the Markov chain |
| k_{ir} | Number of class $r \in R$ jobs in station i |
| $K(\underline{S} E_j) = \sum_{(i,r) \in E_j} k_{ir}$ | Number of jobs in each of the sub-chains in the state \underline{S} , constant in closed networks, $j = 1, 2, \dots, m$ |
| $K(\underline{S}) = \sum_{j=1}^m K(\underline{S} E_j)$ | Number of jobs in the network at the state \underline{S} |
| K_j | Total number of jobs in class j in the network, $j = 1, 2, \dots, R$ |
| $\underline{S} = (\underline{S}_1, \underline{S}_2, \dots, \underline{S}_N)$ | Summarized state for closed BCMP network |
| $\underline{S}_i = (k_{i1}, k_{i2}, \dots, k_{iR})$ | Number of jobs in each class at station i for closed BCMP network |
| V_{ir} | Mean system time for class r jobs in station i (mean time span from the arrival of job to station i to its completion in that station) |
| λ_{ir} | TP of class r jobs at station i |
| L_{ir} | Mean number of class r jobs at station i |

Furthermore, for defining the condition of states in a queueing network the type of stations plays a crucial role. There are several types of stations that are directly related to the

distribution of service times for each class of jobs and influence the processing of them. The regular types of stations are 1) M/M/n-FCFS, 2) M/G/1-PS, 3) M/G/∞, 4) M/G/1-LCFS-PRE, which have different complexities in calculating parameters of BCMP networks.

Basically, BCMP theorem for open, closed, and hybrid networks with stations out of the four above mentioned can be described by the product form (2.5.44) for probabilities of states in different stations.

$$P(\underline{S} = (\underline{S}_1, \underline{S}_2, \dots, \underline{S}_N)) = \frac{1}{G(\underline{K})} d(\underline{S}) \prod_{i=1}^N F_i(\underline{S}_i) \quad (2.5.44)$$

where $G(\underline{K})$ is the normal constant. Since the sum of all probabilities is equal 1 in stationary state then:

$$G(\underline{K}) = \sum_{\sum_{i=1}^N \underline{S}_i = \underline{K}} d(\underline{S}) \prod_{i=1}^N F_i(\underline{S}_i) ; \underline{K} = (K_1, K_2, \dots, K_R) \quad (2.5.45)$$

where $d(\underline{S})$ is dependent on the number of jobs in the network (2.5.46):

$$d(\underline{S}) = \begin{cases} \prod_{i=0}^{K(S)-1} \lambda_i & ; \\ \text{arrival process at entrance of open network} \\ \prod_{j=1}^m \prod_{i=0}^{K(S|E_j)-1} \lambda_i(i) & ; \\ \text{arrival process at sub-chain in open network} \\ 1 & ; \\ \text{closed networks} \end{cases} \quad (2.5.46)$$

In addition, calculation of $F_i(\underline{S}_i)$ is sometimes quite complex and is dependent on type and state of the stations. For instance, consideration of total state space in different problems alternates the volume of mathematical operations in various algorithms for computing performance measures, e.g., load, TP, mean queue length, and mean system time. However, out of the different types of stations, the current study proceeds only with M/M/n-FCFS type for all stations. The advantage of this specific type is its simplicity in calculation algorithm besides its common application in manufacturing industries.

In the specific type of stations for calculating the performance measures following equations hold true.

$$V_{ir} = \frac{L_{ir}}{\lambda_{ir}} = L_{ir} \frac{G(K_1, \dots, K_R)}{G(K_1, \dots, K_r-1, \dots, K_R) e_{ir}} \quad (2.5.47)$$

$$W_{ir} = V_{ir} - \frac{1}{\varepsilon_{ir}} \quad (2.5.48)$$

$$L_{q_{ir}} = \lambda_{ir} W_{ir} \quad (2.5.49)$$

Nonetheless, for calculating these parameters for closed networks two algorithms are famous: mean value analysis (MVA) and convolution [355]. Application of the convolution algorithm is mainly used for evaluating the normalization constant G , while MVA directly aims to calculate the expected values of performance measures in equilibrium [356]. Since the performance of production mechanisms can be fairly well estimated by the mean response time (sojourn), TP, and mean queue length, MVA algorithm seems a reasonable method to solve BCMP networks problems in this work. This algorithm is concisely explained below.

Mean value Analysis: works based on equilibrium in closed networks as first in 1980 Reiser and Levenberg introduced in their paper [357]. The algorithm does not require calculating the complex normalization constants and product terms, while still is applicable to queuing models with product form and non product form solutions, particularly for abundant chains and jobs networks. Nevertheless, the requirement of large memory in the calculation and dependency of final results to the intermediate ones are the weakness of this algorithm. However, its iterative algorithm simplifies the process of calculation and after some iterations, it leads to good answers.

Following equations reflect the MVA recursive algorithm in a general form with different job classes and for every type of saturations (as mentioned). Always, the commencement of the algorithm is with no queue $L_i(0)$ and one job $k = 1$ that step by step number of jobs increases to $k = K$. It is noticeable that for the sake of simplicity the equations used in the algorithm are only for stations with one sever. Table 8 shows the respective notations used in the general form of MVA algorithm.

$$V_i(k) = \begin{cases} \tau_{ir} (1 + L_i(\underline{k} - b_r)); & \text{for stations type 1,2,4 } (n_i = 1) \\ \tau_{ir} & ; \quad \text{for stations of type 3} \end{cases} \quad (2.5.50)$$

$$\lambda_r(\underline{k}) = \frac{k_r}{\sum_{i \in Q(r)} V_{ir}(\underline{k})} = \frac{k_r}{\sum_{i=1}^N V_{ir}(\underline{k})} \quad (2.5.51)$$

$$L_{ir}(\underline{k}) = \lambda_r(\underline{k}) V_{ir}(\underline{k}) \quad (2.5.52)$$

$$L_i(\underline{k}) = \sum_{r \in R(i)} L_{ir}(\underline{k}) = \sum_{r=1}^R L_{ir}(\underline{k}) \quad (2.5.53)$$

$$P(\underline{k}) = \frac{1}{G(K)} \prod_{i=1}^N \tau_{ir} \quad (2.5.54)$$

Table 8: Used notations in general form of MVA algorithm.

| Notation | Description |
|----------------------------|--|
| K | Number of available jobs in network, $k = 1, 2, \dots, K$ |
| $\lambda(k)$ | TP for k circulating jobs (using little's law) |
| $\lambda_r(\underline{k})$ | TP in chain r with population \underline{k} in network |
| $V_i(k)$ | Average sojourn time (response time) in station i |

| | |
|--|--|
| | for k jobs in network |
| $V_{ir}(\underline{k})$ | Average system time of a job in chain r at station i between two consecutive visits of an arbitrarily selected station i^* |
| $\mu_i(k)$ | Service rate in station i , dependent on number of jobs |
| L_i | Average number of jobs in station i , $i = 1, 2, \dots, N$ |
| $L_i(\underline{k})$ | Average number of jobs in station i with population \underline{k} in network |
| $L_{ir}(\underline{k})$ | Average number of jobs in chain r in station i with population \underline{k} in network |
| $L_i(k - 1)$ | Average number of jobs in station i when one job is less in network, (network in view of that respective job/customer) |
| $L_i(\underline{k} - b_r)$ | Average number of jobs in station i with one job less in chain r |
| $\underline{k} - b_r = (k_1, k_2, \dots, k_r - 1, \dots, k_R)$ | Populations vector from network with one job less in chain r |
| $\tau_{ir} = \frac{e_{ir}}{\varepsilon_{ir}}$ | Total service time of a job in chain r at station i |
| $e_{ir} = \sum_{j=1}^N e_{jr} p_{jr,ir}$ | Relative arrival rate of jobs in chain r at station i |
| $\sum_{i=1}^N V_i(k)$ | Total system time for stations with k jobs in network in a single chain |
| $Q(r)$ | Set of stations visited by chain r |
| $R(i)$ | Set of chains that visit station i |
| $r = 1, 2, \dots, R$ | Counting index for chains |

As in the section of the closed-loop system has been reviewed, there exists several researches in the field of material flow control by means of closed-loop mechanisms. Explicitly, those systems which follow the principles of material pull control configure closed-loops in transferring materials between the point of origin and the point of consumption, apart from the scope of both points. Traditionally, material flow control structures have been analyzed by queuing theory, since they absolutely represent the arrangement of queuing systems as jobs, servers, and buffers.

Now, the combination of the queuing theory and the closed-loop material flow in flexible shop floors builds up closed queuing networks with specific characteristics in the analysis. In particular, the Kanban, the Conwip, and the Polca are briefly discussed in the current study, which they resemble closed queuing networks in their performances. The analysis of such closed queuing networks gives rise to better understanding the dynamism of such flexible systems with varying job classes and employment of autonomous objects.

4.5.4 Contribution of the queuing theory to Lpallets

It is realized when there is a need for sensitivity analysis in performance of Lpallets within an assembly line, queuing theory has the capability of modeling assembly lines in either form of closed or open network. In order to control the general plausibility of autonomous

objects performance, which have the mission of real-time scheduling and control in a decentralized structure, queuing theory can model the system and approximate the general expected records of that. In fact, sensitivity analysis is one capability of queuing theory in modeling complex interactive systems including servers, buffers, and customers. Generally, sensitivity analysis can be explained as the study of potential changes happening to any system with uncertain variables and their effects on conclusion and output of the system, or in general their influence on the system's behavior. There are several methods and tools for sensitivity analysis like queuing theory [358] [359].

5 Experiment Scenarios with Simulation

This chapter includes several experiments all based on a discrete event simulation software (called Plant-Simulation package) to evaluate the claimed assumptions for superiority of the autonomy in logistics. The contributions of the autonomy paradigm to conventional logistics processes are justified in this chapter. In fact, the main contribution of the autonomy paradigm to the phenomenon of dynamics in logistics, from different points of view, is experimented here. In particular, at the final sections of this chapter, the novel concept of Lpallets is directly evaluated in some specific experiments. They deal with real-time scheduling problem in alternative assembly shop-floors.

5.1 Integration of Lean-Agile Experiments with Autonomy in Supply Chains

This experiment proceeds with the common aspects of lean, agile and autonomy paradigms in a generic notion. It is tried here to approximate the three concepts in the way of improving the general performance of inbound as well as outbound logistics. After a short introduction to the mutual definitions and tools of each concept, the contribution of autonomy in fulfilling the targets of lean and agility is experimented in the form of a simulation scenario.

5.1.1 Introduction of the Experiment

Appearance of new constraints and complexities on manufacturing systems, competition in markets, customer fulfillment, and resources have brought about several paradigms and concepts to keep industrial enterprises and sectors alive. Following deployment of lean concepts into pioneer industries [360], it was distinguished that sometimes leanness, including its zero inventory approach, is not capable enough of achieving its objective. This is particularly true, when demand is lumpy and highly varying as a result of new business environments. For this reason, new production systems were introduced, which are more flexible and capable of meeting fluctuating demands on time with close adherence to desired products. Consequently, the flexible manufacturing system, the reconfigurable manufacturing system, and some other implications of agility concept have been introduced.

Nowadays, it is known to businesses that one of their major competitive advantages depends on their SC structure and how they manage it [361]. On a broader scale, lean concepts can be accomplished for make-to-forecast (MTF) or MTS supply strategies under a reliable demand forecast, whilst the agile system can be employed for MTO strategies with the quick-response ability, when demand is uncertain and difficult to forecast [362]. Both, lean and agile paradigms are accompanied with several characteristics and targets, which can be achieved by several tools and concepts.

For lean manufacturing, because of its precedence, some adequate methods and tools have been introduced that guide companies to the achievements. However, the core of the concept is independent of the tools (e.g. leveling and sequencing, one-piece flow, JIT, Kanban, continual improvement, Kaizen, flexible capabilities value stream mapping, and automation, see [363] [364]). In lean systems, emphasis is placed on efficiency and cost reduction, although there are some additional indirect benefits (e.g. lean culture). For agile systems the core concept deals with increasing flexibility that makes SC responsive to oscillating demand with reduced lost-sales. There exist still some studies that are conducted on methods and tools to make production systems agile. These contribute to the realization of the main principles of this concept (i.e., virtual manufacturing, agile production design, and knowledge management [364]). Meanwhile, autonomy in functions and decisions is claimed to be a practical method for more flexibility, agility and lean targets.

Along with the introduction of new methodologies and concepts, the autonomy paradigm has become an attractive approach for scientists to tackle the complexities and dynamics embedded in the supply chains and their related processes under uncertain circumstances [13] [365]. According to Scholz-Reiter et al., [52] as a general term, autonomy means: “the independence of a system in making decisions by itself without external instructions and performing actions by itself without external forces”. As a favorable paradigm expanding over leanness and agility, autonomy may be useful to elaborate the targets of the two mentioned concepts. The complementary performance of these three concepts is manifested when they are applied in a supply chain or production network working under a dynamic environment.

5.1.2 Agile Logistics

Nowadays, it is well known to enterprises that turbulent demand and volatility are the inseparable conditions in global markets. Market uncertainty and shortened product life-cycles are faced in such a competitive environment. These force a trade-off between the paradigms of economies of scale and economies of scope in confronting the market demand as well as suppliers’ efficiency and effectiveness targets.

Agile logistics, and its principles, have been applied to supply chains following the flexible manufacturing system. Agility is an organizational oriented and business-wide capability with the targets of greater responsiveness, customization and flexibility, that embraces organizational structures, information systems, logistics processes, and, in particular, mindsets [366]. In other words, “Agility can be considered as a need to encourage the enterprise-wide integration of flexible and core competent resources so as to offer value-added product and services in a volatile competitive environment” [364]. Whereas lean principles can be part of agile systems, there are some circumstances that lean fails in facing the customer requirements at the right time, volume, and variety as well as even its effectiveness targets in supply chains; like the vehicle manufacturing case by Christopher [366].

By evolving agile manufacturing, several tools and techniques have been introduced, as practical ways, to realize agility in supply chains. Network management, knowledge management, mass customization, dynamic enterprise reconfiguration, virtual enterprises, interoperable systems, agile human resources, value chain integration, concurrent engineering, and agile technologies are some instances of those techniques [366], [367]. Some of them are still in development phase, others already have been installed.

Furthermore, contribution level of those techniques to agility is yet different and may be ambiguous. There have been several researches over practical techniques and tools to obtain relevant capabilities and abilities to make manufacturers agile in their performances [367], [368]. Now, imagine how complex the logistics processes of an entire supply chain could be to be undertaken by those techniques in order to make flexible behaviors and real-time decisions. Scholz-Reiter *et al.* [20] and Duffie *et al.* [127] have suggested the new approach to reduce complexity in supply chains and manufacturing as:

decentralized autonomous control for logistics objects instead of the conventional hierarchical control. This contribution is broadly discussed before.

5.1.3 Autonomous Control System in Logistics

Autonomous control (AC) has shown its capabilities in virtual experiments and mathematical calculations in bringing the required flexibility, and real-time performance that an agile system needs [369] [370]. On the other hand, its contribution to lean targets like enhancement in utilization, and reduction of WIP make the paradigm quite compatible with the both lean and agility paradigms in a favorable manner. There are several autonomous control methods for product routing between logistics means and process priority (e.g. production lines, roads, plants, etc.). For example, queue length estimator (QLE), Pheromone, earliest due date, are some methods [126] [370] [371] [372]. In this experiment, it is decided to apply QLE for its easier and understandable operation. It is noticeable that AC is introduced versus conventional systems (Conv).

QLE method gives to products the capability of locally estimating the next queue length plus the processing time for each successor (station). Then the product can autonomously make a decision for its next processing destination. Briefly, the advantage of QLE is that in each decision point the decision maker compares all precise queue length and correspondingly the waiting time of all parallel queues. This method leads to smoother flow of material, less processing time, and avoidance of blindly waiting in queues (as a waste in lean), specifically, when there is a breakdown in a station (for more information of QLE see [369] [372] [373]).

5.1.4 Logistics Performance Measures

In general, logistics operations have a very crucial role for businesses to be successful in the growing global competition. Nonetheless, performance of logistics objectives in SC is full of conflictions and contradicted desires. Fulfillment of one of the aspects could lead to abortion of the other ones. This conflict is called by Gutenberg “dilemma of operation planning” [374]. In order to optimize logistics operations of industries, performance of the operations should be evaluated. In doing so, several measures and criteria have been considered to estimate superior results of different experiments. Here, the following factors are considered to estimate the performance; throughput time (as a factor of responsiveness in agility), utilization (as a factor of waste elimination and value-adding in lean), WIP (as a factor in lean), schedule reliability (as a factor of responsiveness and agility). By considering these measures and their interactions, performance of the applied strategies will be more apparent. Indeed, these measures are the illustrating factors to define the degree of achievements in Lean and agile targets.

5.1.5 Push vs. Pull System

In general, Kanban reflects a pure pull system, while Conwip and Polca are two other systems, which employ both push and pull concepts. These techniques were basically initiated for shop-floor applications, but their mechanisms are extendable throughout SC. Typically, there are two general material flow strategies in supply chains. The first one is

push strategy, which can support MTS systems and is dependent on demand forecasting. This strategy is more efficient and easier to realize MST system. With this respect, capacity utilization is quite high, because of in advance planning (predefined logistics operations). It is more suitable for mass production or rather constant (stable) demands. Nevertheless, it suffers from some shortcomings in complying with new logistics requirements. Accordingly, its mechanism is usually not compatible with the new targets in logistics, like less WIP, and may reflect over production and less flexibility in plan or schedule. However, the second strategy is material pull, which is triggered by (internal or external) customer orders and is based on MTO / ATO systems. Normally, in MTO/ATO orders are customized, thus, final assembly is always postponed to concretize the individuals' orders. Indeed, the later system can be partially suitable for agile principles as well as for lean. In pull systems storage of WIP and inventory volume is normally constant and low (supermarkets instead of inventories), obsolete material is avoided, mass customization approach is facilitated [375], and flexibility, to meet demand fluctuations, is increased.

Here, it is noticeable that pull systems have some controversial aspects in terms of flexibility and responsiveness. In other words, although pull system can comply with customized and individual orders, since orders trigger the productions, but the lead time of customer orders is higher than push systems, and this must be accepted by customers to keep the satisfactory responsiveness. Then in this manner, the JIT technique is quite helpful, in its absolute performance, to reduce WIP and stick to individual orders. Moreover, idealistically, by an absolute JIT performance no demand forecast is needed. Accordingly, a highly flexible logistics system with autonomous processes may comply with the mentioned characteristics. It is believed that in a highly flexible system responsiveness is so high so that every logistical action corresponds to a specific order, since the system can meet them on time. Then the use of autonomous control makes sense.

However, pull systems have some drawbacks. These include: increased risks in material procurement, higher lead times for customer orders, fragile continuous material flows, in case of sudden disturbances (e.g. machine breakdowns), and stock-out situation. The leagility concept divides supply chains into two parts. One part is upstream from DP with a push system and the other part from DP in downstream with application of pull system. This strategy uses the benefits of both lean and agile principles respectively push and pull systems. However, these claims are partially examined in the following simulation scenario of an exemplary SN with some metrics, which are pertinent to lean, agile, and logistics in general, see Figure 70.

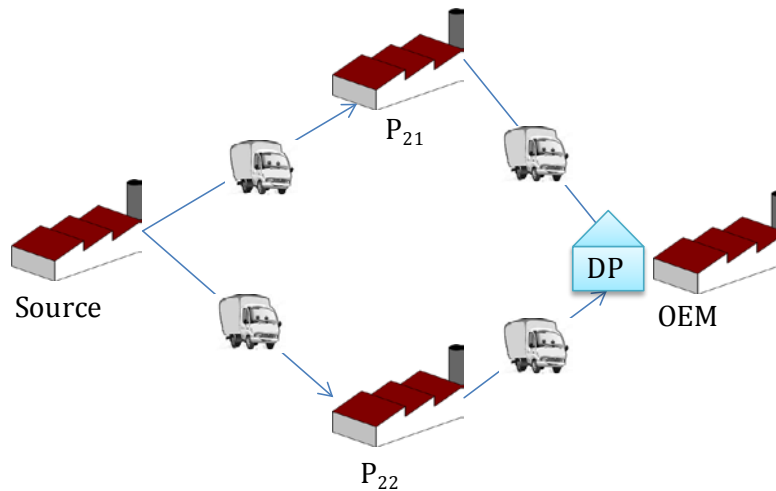


Figure 70: Production network scenario.

Furthermore, in macro perspective of SN, for reducing the bullwhip effects and fluctuations in material flows, some control policies toward hybrid strategies are already developed, e.g., leagility. Accordingly, in particular, application of Conwip control system seems suitable for arranging the both sides of supply and demand in equilibrium. This specification provides a basement for adopting autonomy in logistics networks. For instance, by using this policy, a plant, as a member of supply network, is able to monitor its situation in terms of demand as well as supply rates. Therefore, this monitoring brings some independencies to that member to control its entrance and exit inventories. This could be done autonomously without being dominated by the predecessors. This autonomous plant has the authority for asking more or less supply, based on its order rate.

5.1.6 Simulated Scenario

In the simulation model, a special leagile supply chain scenario has been assumed with fully coupled plants that this resembles a production network. This network is chosen to show the characteristics of autonomous control in logistics concerning some waste aspects (less WIP, high utilization) as well as agility factors (less TPT and less customer lead time). Three steps are supposed for the network, with one source plant in the first stage, two parallel plants of identical capabilities in stage two, and one original equipment manufacturer (OEM) in stage three. The flow of products from stage one is equal in either plant in stage two. For making the model easier to understand, and undertaking the postponement concept, the DP is located at the entrance of OEM. Thus, demand penetrates up to this point, i.e., from the source up to DP push system and for the rest of the chain pull system (as Conwip) are applied. In the Conwip system, there are three types of pallets (each 25) for each product type (there are three types of products to produce). In this mechanism, for each order one pallet will be loaded to the exit of DP to carry one piece of the respective product. This is a one-piece flow in lean concept. It should be mentioned that the number of pallets, product types, and pallet-size (lot-size), each has a different effect on logistic performances, which are evaluated in another experiment later. However, these values are empirically identified and left constant in this experiment, in order to be easier to illustrate the results. Inside each manufacturing plant, a flexible flow-shop

production system is modeled as a (3×3) production line matrix. In other words, each of the three stations in a column is connected to three successors (stations) in the next column. And each column of stations has to be met by each product only once. Table 9 shows the cycle time of each station for each product in the production matrix for each plant. The performance measures inside each plant are considered as local factors and the measures for the entire network are used to describe the global behavior.

Table 9: Cycle times for each station for each product type in each plant.

| Processing Times [H:Min] At Each Plants | | | | | | |
|---|----------------------------------|-------|-------|----------------------------------|-------|-------|
| Plant | P ₁₁ ;P ₃₁ | | | P ₂₁ ;P ₂₂ | | |
| Line Type | 1 | 2 | 3 | 1 | 2 | 3 |
| 1 | 02:00 | 03:00 | 02:30 | 04:00 | 05:00 | 04:30 |
| 2 | 02:30 | 02:00 | 03:00 | 04:30 | 04:00 | 05:00 |
| 3 | 03:00 | 02:30 | 02:00 | 05:00 | 04:30 | 04:00 |

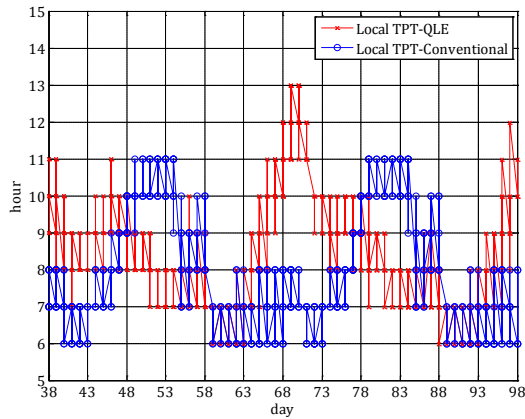
Each two plants are connected via a truck driving with a velocity of 70 km/h. It takes four hours for each round trip, since the distances are 140 km. The trucks do not pause during their journeys. Therefore, the carrying load of the truck varies each time concerning the delivery rate. It should be mentioned that the trucks return empty from their journeys, so products can meet each plant only once and move in one direction.

5.1.7 Simulation Run and Results

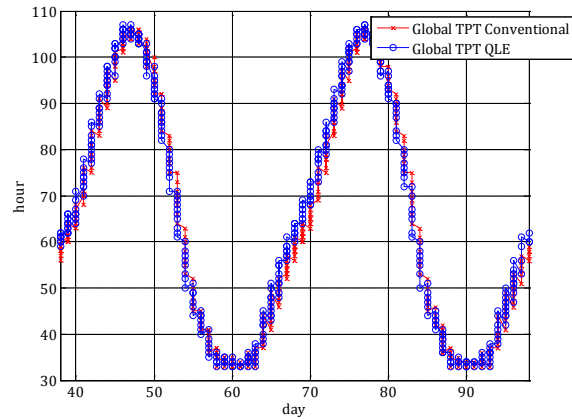
To show the compatibility of the three paradigms (i.e., lean, agile, autonomy) some criteria of each are selected to be represented on the resulting figures. Here, material load sequencing and leveling, TPT, utilization, and also standard deviation (STD), besides customer lead time—as schedule reliability factors—are chosen. In scenario 1, results are sorted into four different experiments to show the performance of AC and Conv under fluctuating demand (with and without sequenced loads). The chosen AC for logistics objects is queue length estimator. QLE gives the ability to products and pallets to make real-time decisions for their routes according to queue of each line. The experiments are as follows:

Sinusoidal push and pull (both load and demand) rates, which is represented as fluctuating or seasonal effect, $\lambda(t) = 0.4 + 0.15 \cdot \sin(t + \varphi)$. The mean value of the sine equation (rates) is 2:30 h. This flow rate holds true for the three types of products, but with a $(1/3 \times \varphi)$ phase shift for each type (i.e., $\varphi=0, 2\pi, 4\pi$). Thus, two scenarios are considered here. Firstly, simulations are without sequenced material loads, just by loading the three product types simultaneously under QLE and Conv control, see Figure 71a and Figure 71b. In Conv products just get processed on the lines with the least cycle time for the corresponding product type. It totally follows the predefined plan and schedule to control. Secondly, simulations are with sequencing the loads according to demands' sequences (Figure 71c, Figure 72a, Figure 72b, Figure 72c, Figure 73a). It should be mentioned that QLE method, from one point of view, does the task of leveling the lines at real-time, by dispatching products to stations with less waiting time in queue and bottleneck prevention.

a) Local TPT (for OEM) under sinusoidal demand without sequencing, under Conv and QLE systems: mean value for Conv=8 hour, QLE=8 h, with STD for Conv=1:31 h, QLE=1:26 h



b) Global TPT under sinusoidal demand without sequencing, under Conv and QLE systems: mean value for Conv=67 h, QLE=67 h, with STD for Conv=25:15 h, QLE=25:16 h.



c) Local TPT (for OEM) under sinusoidal demand with sequencing, under Conv and QLE systems: mean value for Conv=7 h, QLE=9 h, with STD for Conv=0:42 h, QLE=1:00 h.

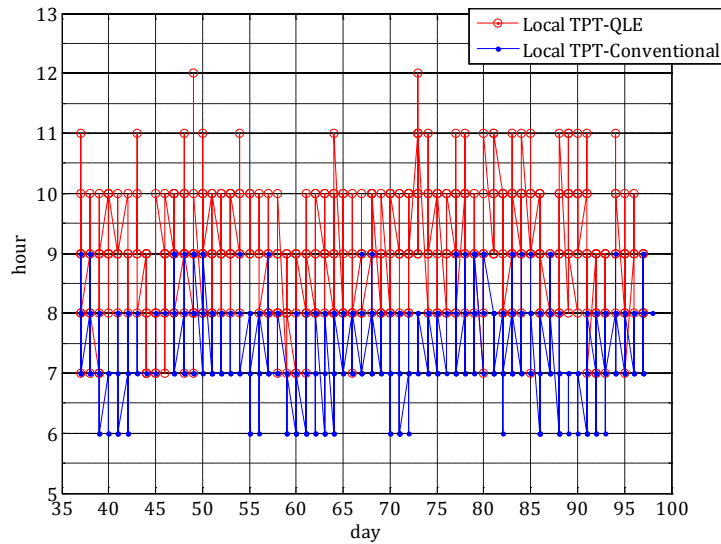


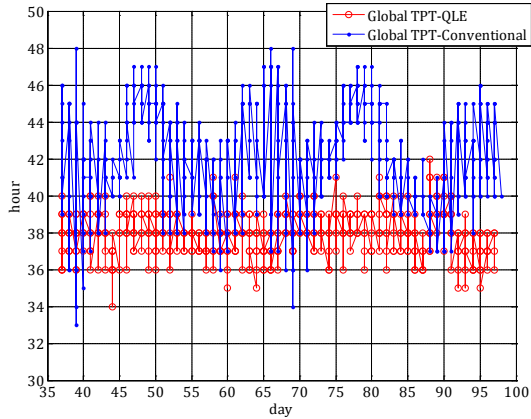
Figure 71: Local TPT and global TPT in alternative scenarios.

As it is shown in Figure 71a, Figure 71b, Figure 71c, the performance of QLE is not better than Conv. Despite the DP separation task, OEM is still dependent on the incoming rates into DP; because WIP is not high enough to fulfill demands on time. In this case, concerning the damping effect of transporters and previous plants, the replenishment rates for OEM is constant (and in average under processing capacity of OEM lines). Thus, the rate of processed products is constant too (due to limited numbers of pallets and constant replenishment rates). So, again, under constant rate Conv obviously works better.

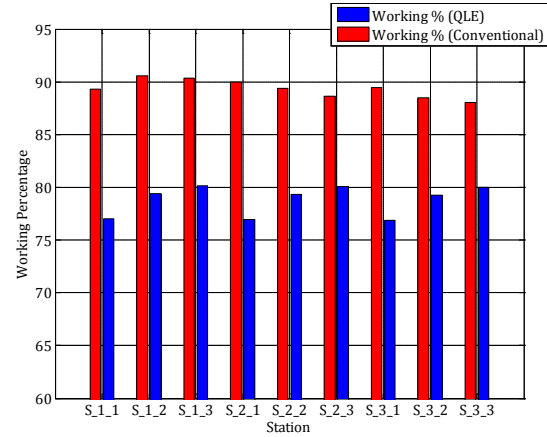
In fact, despite the sinusoidal load, with simultaneous load rates, logistics shows a static behavior with constant pulse (pace). When three loads pulsate concurrently, the first tier of logistics is changed to bottleneck and the rest of the tiers have a constant delivery rate. Thus, Conv works the same or may be better than AC under a stable circumstance. However, other performance measures like higher utilization (with constant WIP) and responsiveness are much better, when the system uses AC. As Figure 72a shows, with the use of QLE, Global TPT has lower mean value and STD. It is the same for utilization in

Figure 73b that AC performs better as well as customer lead times in Figure 72c with QLE under sequencing that has quicker respond to customers.

a) Global TPT under sinusoidal demand with sequencing, under Conv and QLE systems: mean value for Conv=42 h, QLE=38 h, with STD for Conv=2:43 h, QLE=1:00 h.



b) Utilization percentage of stations in OEM for Conv and QLE systems with sequenced load.



c) Customer Lead time for Conv. and QLE, under sine demand and load.

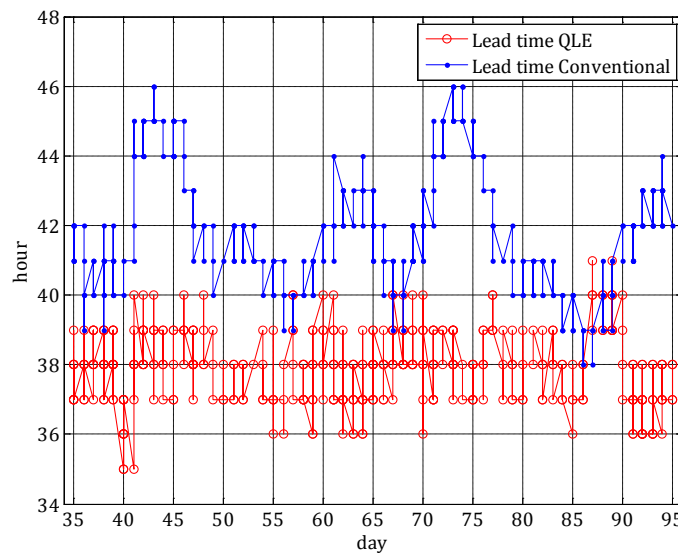


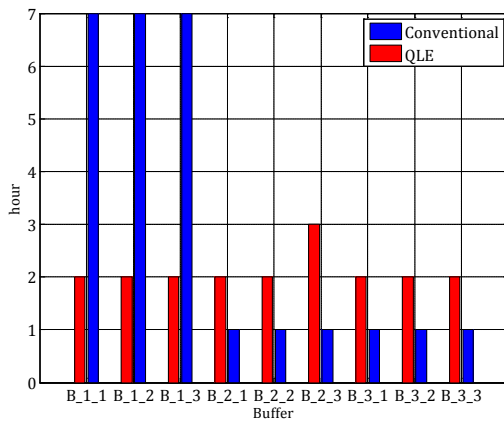
Figure 72: Global TPT, utilization and customer lead time under alternative scenarios.

Here, lead time, is the gap between customer order and its fulfillment. This represents the responsiveness factor of the scenario. The simulations ran for 100 days that the last 60 days of them are depicted on all figures. The results show that when there is a phase shift between supply rates of products, exploitation of AC makes an improvement into the system. For showing this a further experiment is done in follows. However, when replenishment rates are simultaneous and not in sequence of fluctuating demand, then Conv could make more sense.

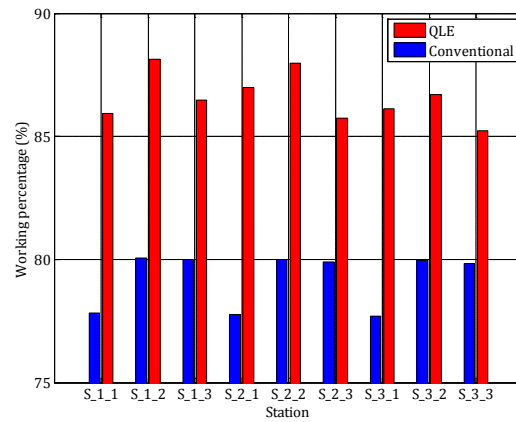
Push of materials with semi-constant loads following the normal distribution as load rates for each product type is scenario 2. Demand follows still the same sinusoidal behavior. The push load has mean value and STD of ($\mu=2:35$ h, $\sigma=1$ h), which is a bit more than the mean value of sine demand. This is because of shortage avoidance in DP. This simulates constant

loads before DP and fluctuating demand after DP, as agile SC support that. Figure 73a represents WIP in OEM lines. The spread of WIP is homogenized with QLE. Figure 73c shows the local TPT in OEM for scenario 2. The global TPT in this case is increasing in a linear manner. Because the push rate is higher than pull rate, thus the DP collects more inventories and, thus, more global TPT. It means the replenishment rate is higher than demand rate. This is the evidence of material obsolescence. However, the purpose of this experiment is to show the capability of AC in a chaotic situation, e.g., replenishment is equal or higher than demand. In scenario 2, the DP has enough inventories to supply pulled demand, so QLE performs much better under turbulent (sinusoidal) demand rate. Less TPT and higher utilization are the goals, which are obviously achieved here, see Figure 73b.

a) WIP of buffers in OEM for Conv and QLE systems, under sine demand and stochastic load.



b) Utilization percentage of stations in OEM for Conv and QLE systems, under sine demand and stochastic push.



c) Local TPT (for OEM) under sinusoidal demand with stochastic push load by normal distribution.

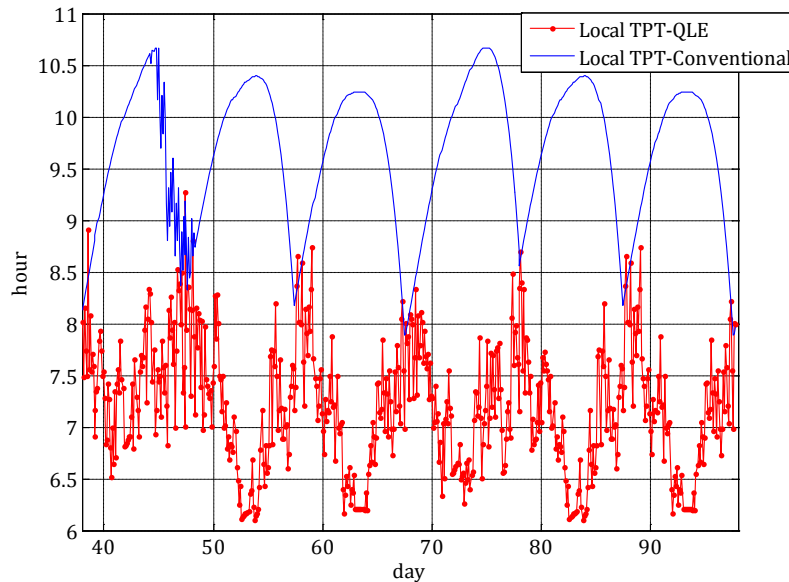


Figure 73: WIP, utilization, and local TPT under alternative scenarios.

5.1.8 Conclusion of the Experiment

After a short introduction to lean, agile and autonomy paradigms, simulation results have illustrated the complimentary aspects of the paradigms and their correlations. For this

purpose, logistic performance measures are considered to show the trade-off between the employed strategies' performances. For example, TPT and customer lead time represent the quickness and responsiveness of each method (Conv or QLE). Also, percentage of utilization and WIP numbers defined the efficiency and effectiveness of the experimented methods. Just by these criteria the ratio of autonomy to agility and lean concepts can be clarified.

Whereas previous works illustrated the superior performance of autonomous control methods in pure push systems, these experiments' results demonstrate the importance of improvement in autonomous control methodologies in order to suit the autonomy paradigm, in particular, to pull systems and alternatively closer to practice. It can be deduced from simulation results that in a leagile network, before reaching DP a conventional production plan can be applied properly. This brings cost efficiency and less setup times e.g., zero changeover percentage. According to the logistic performance measures and the results of this work, autonomy can be employed for optimizing the trade-off between the performance measures. Furthermore, lot-size, which in this chapter has been considered as one piece, and the number of pallets are the other optimizing factors in pull system logistics. Autonomy concepts can deal with flexible lot-sizes and other optimizing factors as well.

The examined autonomous control method at this level of research has been regarded as routing autonomy in SN. However, other aspects of autonomy, besides, the implementation of other lean improvement techniques— like hybrid working cells in cooperation with autonomous parts to bring more comfortable customization and assembly according to real-time orders— could be the other autonomy aspects, to be done in prospective studies. However, in fully flexible SN even DP may be flexible in terms of its location regarding the current strategy to be followed. For instance, the autonomous pallets may take the ratio of supply and demand. Then based on the ratio the pallets decide over push or pull control individually. Moreover, pallets may have flexible carrying size regarding the current demand and order rate. These issues are discussed by Scholz-Reiter and Mehrsai in [48].

5.2 Optimization of Material-Pull in a Push-Pull Flow Logistic Network, using Meta-Heuristic and Fuzzy System

This experiment covers a push-pull system in SN with DP at the entrance of OEM. It is based on the paper presented at “The 1st International Conference on Logistics and Maritime Systems (LOGMS)” [235]. Similarly, the leagile concept is employed for an exemplary SN. The main goal is to show the importance of some decisive factors in such push-pull networks with fluctuating orders as well as supply. Due to high dynamism in the material flow system, the complexity is high as well. Here, uncertainty in processing times and multi-objectives make the problem quite hard to be processes by conventional mathematical programming. Moreover, the objectives are to reduce the average global TPT of the entire network as well as local TPT in OEM, besides, increase of stations' utilization in OEM. Here, with an extension to the previous scenario, the number of pallets, cycling in Conwip part, and size of each pallet, are considered as optimization factors. They directly

affect a smooth material flow through the conjunction point of push and pull (DP). For this purpose, two intelligent heuristics (GA and SA) are employed to find the near optimum values for improving the decision of managers in material handlings. It is noticeable that the heuristics are run in offline simulation, so the simulation days are known. Besides, fuzzy set theory is exploited for two reasons. First, it is used in aggregating multi-objective problem in a normalized unique objective to maximize the satisfaction degrees for all objectives. Second, the fuzzy system is used to cope with uncertainty in recognizing consecutive queue lengths in the assumed flexible flow-shop at OEM.

5.2.1 Hybrid Push-Pull Control

Despite the fact that MRP is a central control system, which pushes materials to downstream of consumption point, in contrary, pull principles are categorized in distributed control systems. Pull systems work based on WIP limitation and current demand of the local working area. Concurrent application of both push and pull systems is a twofold view as: seamless control of material flows and streamlining them. Firstly, employment of push (by central control) defines the release dates of processing in a global context. Meanwhile, pull control operates based on local situations of WIP. Consequently, global and local factors interact with each other. This approach enhances the coordination of the entire logistics system facing dynamics. However, simultaneously, employment of push and pull systems is not necessarily required. Inspired by shop-floors control, some suggested control strategies for logistics networks can be sorted as follows:

- Division of the entire network into two parts as push and pull, which is broadly discussed as Leagile supply chains,
- Employment of both push and pull control systems simultaneously within each member of the network or throughout the whole network, like: Conwip and G-Polca (this type needs high flexibility overall, which is subject to have distributed and intelligent control system) [237],
- Inspired by Polca, dividing the network into paired-cells and applying the material release date by push system as well as WIP limitation by pull cards.

In these listed options, dispatching rules and workload balancing are still challenging issues. However, in this experiment just the first proposed option is analyzed. The downstream in the network with material pull flow is optimized to coordinate the collision point of push-pull flows (DP). Dispatching rule and balancing workloads are chosen to be done based on the autonomous control system, which uses autonomous pallet and QLE method with precise as well as fuzzy estimations. It follows the bottleneck control rule, but based on autonomous objects' decisions and less queue length, see Scholz-Reiter et al. [35]. Moreover, the pull side, which is located in OEM, gets triggered by customer orders that have a stochastic nature with neg-exponential distribution for inter-arrival times between orders, as in practice [376]. The pdf of neg-exponential is like $g(x) = \frac{1}{\beta} \cdot \exp\left(-\frac{x}{\beta}\right)$, with $\beta = 2:50 \text{ min}$. However, the push side depends on the incoming semi-finished products to DP, which is dependent on their supply rate.

5.2.2 Problem Definition

The simulated network is constructed by three steps of processing plants, see Figure 74. In step 1, two plants (P_{11} , P_{12}) are considered to produce three types of raw material in each plant. Each type of raw material has to get assembled with its counterpart from another plant, in the next step. The step 2 has two assembly plants (P_{21} , P_{22}) which have the same processing capability. Therefore, the plants in step 1 are fully connected to the plants in step 2 and products will be allocated to them based on their queue length and bottleneck control concept. The plants in step 2 will transfer their assembled products (which are now just three types) to the final plant called OEM. From sources up to the entrance of OEM products are pushed regarding the forecasted demand and just inside OEM pull principle is applied. This is to meet alternations in demands of the three types over the time horizon.

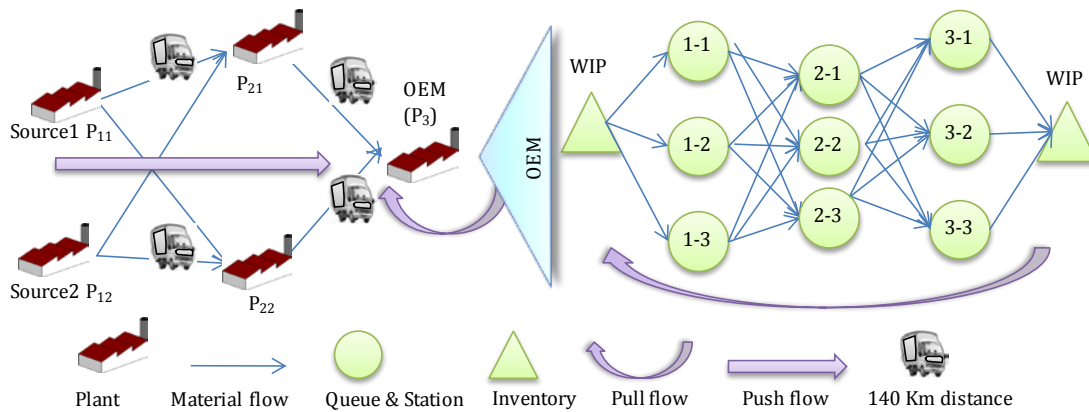


Figure 74: Exemplary push-pull network, with lasting each round trip 4 hours for transporters.

Moreover, for explaining the optimization problem, on the one side, material flow flexibility, in addition to the rate of material push have to be considered. On the other side, the stochastic upcoming orders on the pull side have to be taken into account. For this purpose, the supposed flexibilities in this experiment are autonomous control for pallets in routing as well as flexible lot-sizes and number of cyclic pallets in OEM. Basically, three types of products are assumed in the simulation scenario that each can be carried by respective type of pallets. Here, the processing times in stations follow the normal distribution $N(\mu, \sigma^2)$ that is resembled by triangular fuzzy numbers for estimation. Here, the mean value is equal to the middle range of respective triangular fuzzy number and standard deviation is $\sigma = \frac{\mu}{10}$.

Furthermore, despite three types of final products, each type of product is combined of two raw materials, each coming from a source. However, this stream of flow from sources follows uncertain delivery intervals. So, the stochastic combination of operations and transportations between the network's plants make the supply of semi-finished products, to OEM, fully stochastic natured too. In the same way, demand interval's distribution is stochastic. Consequently, these stochastic features cause a very complex dynamic system with vagueness in real-time control decisions.

However, another great complexity accompanied in this problem is on time arrangement of empty pallets to be available for carrying upcoming orders and products. Since the flow of pushed materials as well as upcoming demands are uncertain and unstable, the number of Conwip carts (pallets here), and lot-sizes can be considered as optimizing factors for making tradeoffs in the flow problem. Nonetheless, their exact contributions to the objective are mathematically unknown in advance. This is a strong reason for employing simulation and heuristic methods to solve this problem.

5.2.3 Applied Genetic Algorithm

In general, the procedure of GA in this study is as follows:

| General genetic algorithm used in optimizing number of pallets and (lot)size | |
|--|---|
| Begin | |
| | <i>t = 0;</i> |
| | <i>initialize new population P(t);</i> |
| | <i>evaluate the fitness value of current solutions (individuals)</i> |
| | while (generation number < 7) do |
| | begin |
| | <i>t = t + 1;</i> |
| | <i>select individuals for P(t) with higher probability from P(t-1);</i> |
| | <i>alter (crossover and mutate) individuals in P(t);</i> |
| | <i>evaluate P(t);</i> |
| | end; |
| end; | |

Here, the roulette-wheel section is chosen as the selection operator. The roulette-wheel function measures a probability of selection for each individual by getting the mean value of the fitness $\left(P_i = \frac{f_i}{\sum_{j=1}^N f_j}\right)$ of an individual in proportion to all observations of the fitness values. Here, N is the number of individuals in current population. Easily, the higher the probability value the more chances have the individuals to be selected.

Furthermore, the specific GA for this problem is supposed to optimize the fitness value, which is a based on a multi-objective function. So, fitness values (called observation) for each individual, in each generation, are to be calculated by following objectives:

$$\left. \begin{aligned} \text{Min } x_1 &= \sum_P \sum_T AGTPT_{pt} + \sum_P \sum_T ALTPT_{pt} \\ \text{Max } x_2 &= \sum_T TD_t \\ \text{Min } x_3 &= \sum_T WIP_T \end{aligned} \right\} \quad (3.2.1)$$

Table 10: Applied notations in the problem.

| NOTATION | DESCRIPTION |
|----------|---|
| <i>t</i> | Product type; <i>t</i> = 1, ..., <i>T</i> ; <i>T</i> = 3 |
| <i>p</i> | Product number ; <i>p</i> = 1, ..., <i>P</i> ; <i>P</i> = depends on 80 Days simulation run |

| | |
|--------------|--|
| $ALTPT_{pt}$ | Average local throughput time (in OEM for type t product p) |
| $AGTPT_{pt}$ | Average global throughput time for type t product p |
| TD_t | Total delivery of product type t |
| WIP_T | Maximum Entrance inventory in OEM for type t |

Nevertheless, these functions are unified to the objective of maximization of satisfaction degrees by following equation (as it was explained in fuzzy mathematical programming chapter). Then the GA procedure starts.

$$Max \min(\mu_{\tilde{a}}, \mu_{\tilde{b}}, \mu_{\tilde{c}}) \quad (3.2.2)$$

The GA continues by selecting parents (by roulette-wheel) for the next generation according to the probability values of each individual. Then the crossover and mutation operations are applied to the parent to breed a new generation. Here, crossover function has the probability of 0.8 and mutation of 0.1, as is common in literature. In the next generations, the procedure is the same. All individuals in a new generation are evaluated unless they have been seen in the previous generations. Totally, GA experiments 110 ($10+5 \times 20=110$ out of $50 \times 10=500$) individuals consist of the couple of lot-size and pallets number, for seeking the excellent performance of the system, see Figure 75.

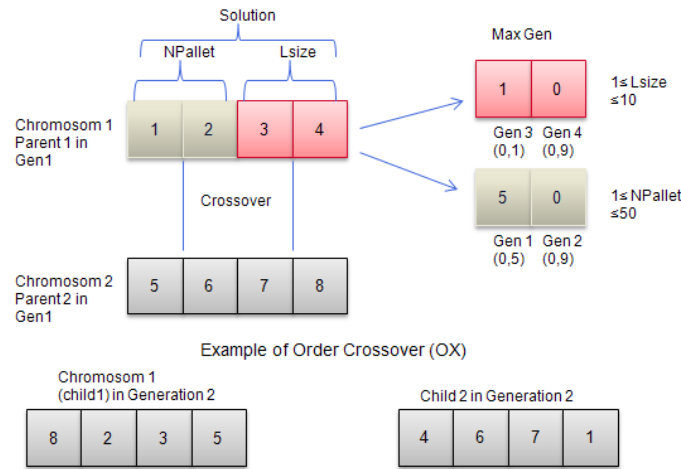


Figure 75: Exemplary performance of the used GA crossover in breeding children for the next generation and encoding.

5.2.4 Simulated Annealing

According to the algorithm of SA in previous chapters, here, the step function in decreasing the temperature Te after each loop follows the function of $Step = \exp\left(\frac{c-1}{\ln(Te/Te_{min})}\right)$. The step function is inspired by literature as well as empirical trials to show the best cooling schedule. Where, Te notices the current temperature, Te_{min} min is the least temperature, and c denotes the cycle number in the loop. This special use of cooling procedure assists the algorithm to avoid local optimum solutions and optimistically escape from local traps towards a global optimum in a given amount of time.

5.2.5 Fuzzy Set

Fuzzy set theory is a powerful set theory for characterizing uncertainty and stochastic nature of practical operations in complex systems like logistics. Practitioners are aware that any human-centered problems in industries, e.g., processing times, due dates, and delivery time, are uncertain in nature, Sakawa *et al.* [179]. Specially, in case of logistics operations, it can be seen that customer orders appear stochastically. Accordingly, the respective information is usually imprecise throughout SN. For this purpose, fuzzy control systems by employing fuzzy numbers, their membership functions, and defining fuzzy inference rules can distinguish the existing uncertainties as well as compromising imprecision. In fact, they suit to vague or ill-defined problems like logistics. In particular, here, uncertainty—e.g., processing times with normal or exponential distribution and ill-defined—in shop-floors or through outbound logistics causes imprecise decisions over material flow scheduling and control tasks. This problem can be solved better by taking into account the fuzzy nature of operations and arranging fuzzy rules for better results in decisions. Respectively, *IF-Then* fuzzy rules reflect the policy of decision makers in terms of the objectives, see Petrovic *et al.* [298]. However, for this experiment, fuzzy set theory just accomplishes two tasks. Firstly, it is used in the form of the inference system to distinguish the least queue length of consecutive stations in the assumed flexible flow-shop problem in OEM. Secondly, it is applied for unification of disparate multi-objects. Each of these applications can be explained as follows.

The fuzzy set is merged to the performance of QLE method for estimating ambiguous queue length of parallel stations, which is explained below. However, ambiguity in the estimation of queue length may have different aspects. Initially, the processing time can have a fuzzy nature instead of crisp value, while the exact information about the number of products and their types in each queue is available for estimation. This case is experimented in this chapter. Moreover, the other vague aspect of fuzzy QLE may be imprecise information about the buffers in front of each parallel station. In this case not only the processing times are imprecise and fuzzy natured, but on the top of that there is no exact information for QLE to make a precise decision about the least queue length station as its successor. The latter case is broadly explored in another experiment in the next chapter.

| Fuzzy queue length estimator algorithm |
|---|
| Begin <i>i</i> =Number of parallel stations for <i>t</i> = 1 to <i>i</i> loop Estimate the queue length of station <i>i</i> : (regarding number and types of products in buffer) Aggregate the fuzzy processing numbers for all waiting products in Queue and station Next Compare the fuzzy waiting times in <i>i</i> station by using ranking metrics Choose the station with least waiting in that as successor end; |

In fact, Several shapes can be used for defining membership functions of fuzzy sets, among them are triangular, trapezoidal, Gaussian, and s-curve [298] [377]. Triangular fuzzy

membership function, because of its simple arithmetic operations, is usually considered for modeling uncertain processing times. However, the processing times in OEM follow a triangular fuzzy numbers as in Table 11 the processing time over the entire network scenario is given.

Table 11: Processing times for each product on each line.

| | PROCESSING TIMES [H:MIN] FOR EACH PLANT | | | | | | |
|---------|---|------|------|-----------------------------------|----------------------|------------------|------------------|
| PLANT | P ₁₁ ; P ₁₂ | | | P ₂₁ ; P ₂₂ | P ₃ (OEM) | | |
| | LINE | | | | | | |
| | DETERMINISTIC VALUE | | | | FUZZY VALUE | | |
| PRODUCT | 1 | 2 | 3 | 1 | 1 | 2 | 3 |
| TYPE 1 | 2:00 | 3:00 | 2:30 | 0:50 | 1:48, 2:00, 2:12 | 2:24, 2:40, 2:56 | 2:06, 2:20, 2:34 |
| TYPE 2 | 2:30 | 2:00 | 3:00 | 0:50 | 2:06, 2:20, 2:34 | 1:48, 2:00, 2:12 | 2:24, 2:40, 2:56 |
| TYPE 3 | 3:00 | 2:30 | 2:00 | 0:50 | 2:24, 2:40, 2:56 | 2:06, 2:20, 2:34 | 1:48, 2:00, 2:12 |

These values are exerted in order to recognize uncertain waiting times and upon them choosing the best route with the least waiting time. This happens by knowing the exact number and types of products in each parallel queue and then just by aggregating them based on the fact of $(\tilde{Y}_1) + (\tilde{Y}_2) = (y_{11} + y_{12}, y_{21} + y_{22}, y_{31} + y_{32})$ in fuzzy set theory. Besides, in order to compare fuzzy waiting times of parallel stations, the pallets have to use some ranking criteria for comparing the fuzzy waiting values, for more information see Sakawa *et al.* [179].

$$\tilde{Y}_1 \geq \tilde{Y}_2 \iff C_1(\tilde{Y}_1) \geq C_1(\tilde{Y}_2) \text{ or } C_2(\tilde{Y}_1) \geq C_2(\tilde{Y}_2) \text{ or } C_3(\tilde{Y}_1) \geq C_3(\tilde{Y}_2) \quad (3.2.3)$$

where $C_1(\tilde{Y}) = \frac{y_1 - 2y_2 + y_3}{4}$; $C_2(\tilde{Y}) = y_2$; $C_3(\tilde{Y}) = y_3 - y_1$.

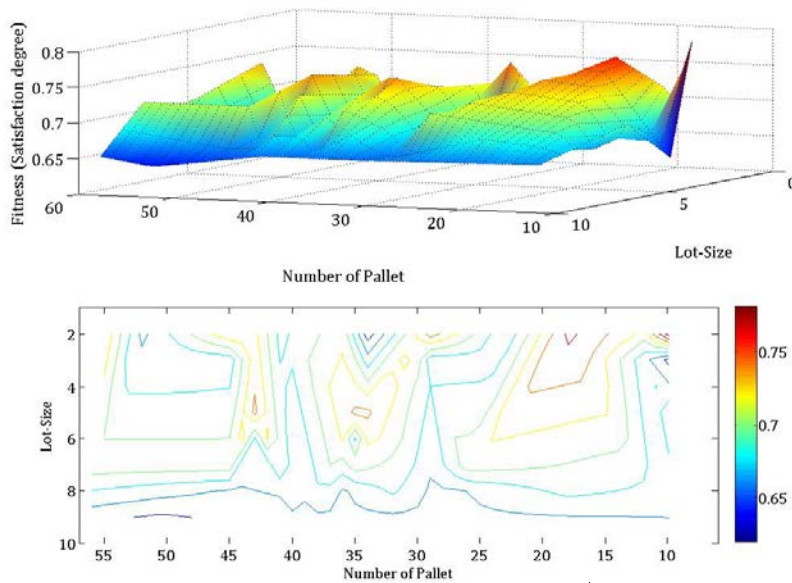
This ranking is to compare different fuzzy numbers in each column of parallel stations to find the smaller one of them. It is directly used in comparing fuzzy parallel queues. Moreover, the three ranking measures are quite relevant when more than two fuzzy numbers are to be compared. For this purpose, each time a pallet compares the three parallel queues, the three fuzzy numbers are compare first by C_1 if the ascending values of C_1 are found, then there is no need to get the values of C_2 and C_3 , otherwise they should be calculated, respectively.

5.2.6 Experiment Results

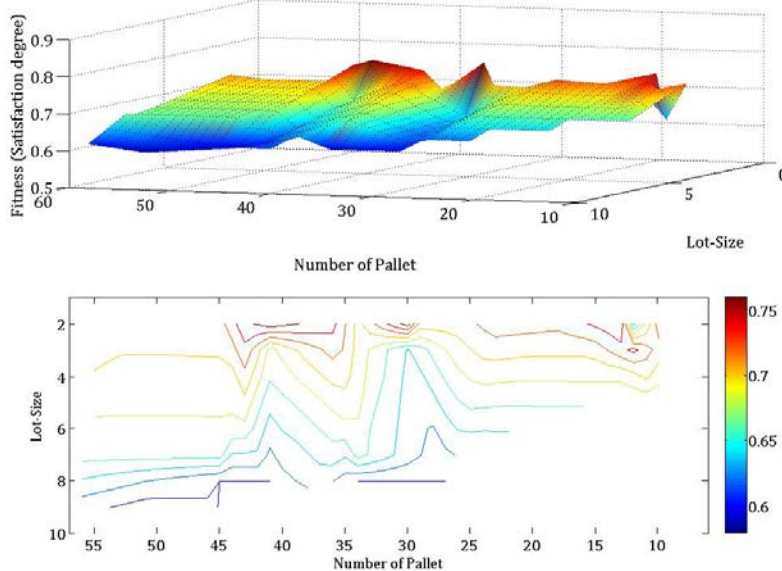
In this section, two alternative outcomes of the simulation are displayed by surface graphs. The two alternatives are as applying fuzzy sets in QLE control and conventional QLE with crisp estimation, in estimating queues' waiting times. However, the processing times are stochastic in all. For better perception of both performance alternatives and in order to evaluate the effect of push flow on the pull section, two supply rates are considered for the source plants in the network to follow the normal distribution and neg-exponential

distribution. Figure 76 in a1 and a2 depicts the search values of GA for the three coordinates as: lot-size, number of pallets, and fitness value; when the flow control does not consider fuzzy sets. In Figure 76a1 supply rate follows neg-exponential distribution ($\beta = 55 \text{ min}$) and in Figure 76a2 normal distribution for supply rate ($\mu = 55 \text{ min}, \sigma = 5 \text{ min}$) is considered. In fact, simple QLE assumes processing times are just crisp, by using the middle value of the normal distribution in processing times. Obviously, in this procedure, the satisfaction degrees are unreliable, fluctuating, imprecise, and, in average, lower than the counterpart experiments with QLE.Fuzzy.

a1) Simple QLE with neg-exp $\beta=55 \text{ min}$.



b1) QLE.Fuzzy with neg-exp $\beta=55 \text{ min}$



a2) Simple QLE with Normal $\mu=55 \text{ min}, \sigma=5 \text{ min}$.

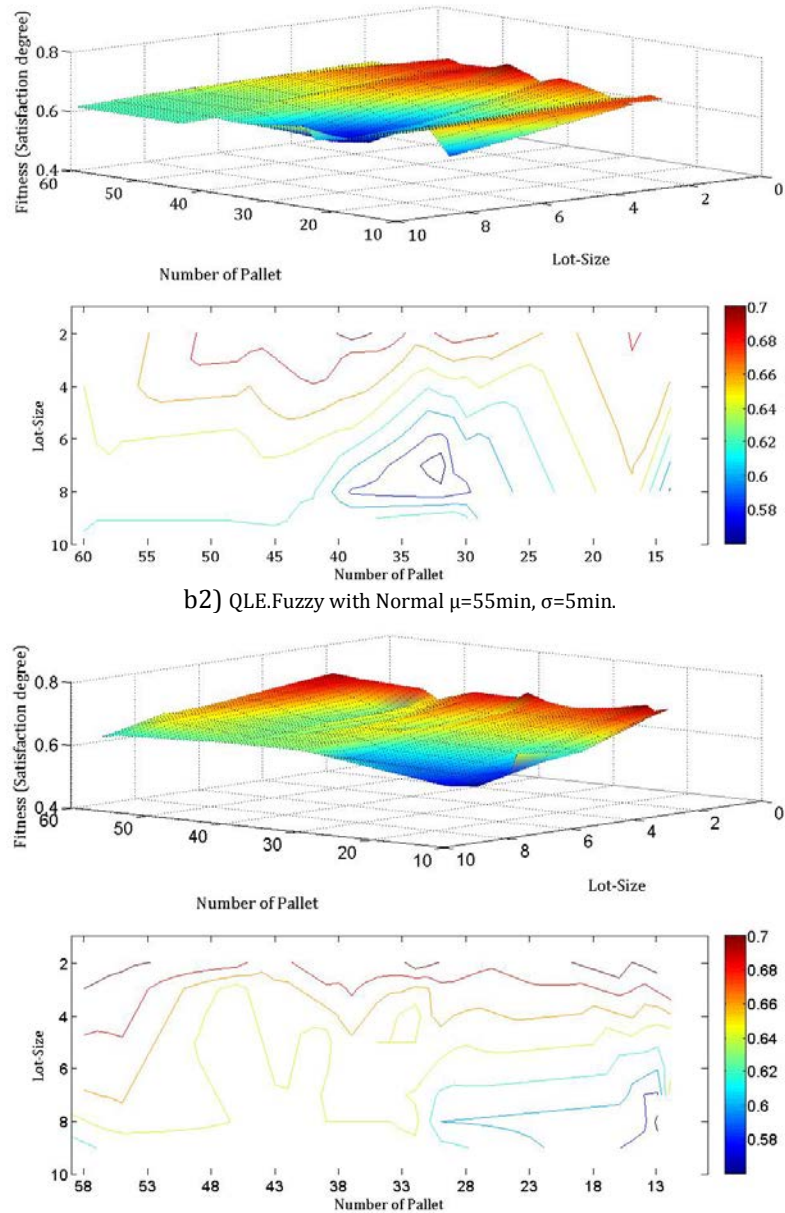


Figure 76: The results for alternative scenarios in the presence of fuzzy sets and without.

On the contrary, Figure 76 in b1 and b2 displays GA search values with the employment of fuzzy sets in comparing uncertain queues' waiting times, respectively, with negative exponential supply ($\beta = 55 \text{ min}$) in Figure 76b1 and normal ($\mu=55\text{min}$, $\sigma=5\text{min}$) supply rate in Figure 76b2. These figures reflect the fuzzy nature of processes and consider the Sakawa ranking criteria. In these cases higher satisfaction degrees in average are achieved, because of better uncertainty distinction in decisions. However, it is obvious that the supply rates with normal distribution have a smoother surface than those with negative exponential. This refers to the higher replenishment rate at OEM, which compensates lack of material in case of lot-sizes >1 . For more results of further alternatives see appendix A.

The results prove that when the system is uncertain using fuzzy numbers and operations performs better than crisp values with their conventional calculations. Finally, the application of meta-heuristics gives the opportunity to a decision maker for adapting its

system to optimality through a broad range of available searched values. The figures show that satisfaction degrees in the presence of fuzzy sets are higher in the same lots-size and pallets' number.

Table 12: Satisfaction degrees in SA for two alternatives with neg-exponential supply in Source plants.

| SA WITH THREE DIMENSIONS | | | |
|-------------------------------------|------|------|------|
| USING QLE.FUZZY WITH NORMAL | | | |
| SATISFACTORY DEGREE | 0.79 | 0.81 | 0.83 |
| NUMBER OF PALLETS | 45 | 46 | 29 |
| LOT-SIZE | 2 | 1 | 3 |
| QLE WITH NORMAL | | | |
| SATISFACTORY DEGREE | 0.71 | 0.81 | 0.81 |
| NUMBER OF PALLETS | 30 | 20 | 18 |
| LOT-SIZE | 5 | 1 | 4 |
| USING QLE.FUZZY WITH NEG-EXP | | | |
| SATISFACTORY DEGREE | 0.73 | 0.74 | 0.75 |
| NUMBER OF PALLETS | 15 | 18 | 27 |
| LOT-SIZE | 3 | 4 | 2 |
| QLE WITH NEG-EXP | | | |
| SATISFACTORY DEGREE | 0.72 | 0.73 | 0.73 |
| NUMBER OF PALLETS | 10 | 29 | 27 |
| LOT-SIZE | 3 | 4 | 2 |

Respectively, the results out of SA (Table 12) can justify the performance of GA, since they are comparable. However, in the case of SA, because of its essence, just the continuously improving results are shown to the simulator, according to the temperature and cooling system. Nevertheless, SA like GA requires several tunings to bring desirable results. In spite of more calculating time, in our experiments SA brought higher satisfaction degrees than GA in case of normal supply in source plants. In contrary, GA brought higher satisfaction degrees in case of neg-exponential supply. This is because of search space.

In conclusion, the main contribution of this experiment approach is to assist managers in making better decisions for such complex problems like the decision over the number of Conwip carts as well as their lot-size. It has been seen here that this decision is fully dependent on the supply and demand rates and may have a very alternating behavior. It is very hard to use conventional mathematical formulas to calculate the optimum values for this problem, while the use of GA or SA can give rise to good alternatives within a relatively short time.

5.3 Toward Learning Autonomous Pallets by Using Fuzzy Rules, Applied in a Conwip System

This section holds the same SN scenario as the one in previous experiment, while it extends the experiment in further aspects. It is based on a submitted paper to international journal of advanced manufacturing by Mehrsai and Scholz-Reiter [378]. The main focus in this experiment is not on the number of pallet but, here, use of Lpallets in finding better routes facing uncertainty is emphasized. In this experiment, several trials are done to underscore the superiority of learning within Conwip closed-loop. In this section, the subjective

algorithms for judgments as well as learning are illustrated. Moreover, by holding the same scenario the problem can be conventionally reduced to a simple flexible flow-shop scheduling problem with minimization of average flow time (or TPT). This objective combines the minimizing of local and global TPT by integrating the waiting time at the entrance inventory of OEM to the flow time through the flexible shop-floor.

5.3.1 Mathematical Programming Representation

The problem can be mathematical modeled by the following programming. However, it is noticeable that consideration of imprecise parameters existing in the simulated scenario is not straightforward. To model the problem is yet easier than solving that conventionally. In addition to the *NP*-hard nature of the problem [379] the stochastic and fuzzy parameters make it quite hard to be solved. Indeed, as mentioned in the relevant section before, mathematical programming with conventional solutions is not suitable for problems with dynamics and uncertainty, since the optimization solvers have static nature. The problem has some real-world specification that requires real-time decision makings. For instance, number of products is not available in advance to be solved statically, so several presumptions are required to solve it conventionally without simulation or heuristics. However, the problem can be fairly good modeled as MINLP like below:

Set:

Products: $j, h = \{1, \dots, N\}$

Family: $f, q = \{1, \dots, 3\}$

Column: $c = \{1, \dots, 3\}$

Station: $s = \{1, \dots, 3\}$

Parameters:

V_{sc} No. of parallel stations (s) in column (c)

α_f Importance weight of family f

Stochastic and fuzzy parameters:

r_{jf} Release time of product (j) in family (f) to the shop-floor (after entrance inventory)

e_{jf} Entrance time of product j in family f shop-floor (before entrance inventory) following neg-exponential distribution

$\tilde{p}a_f$ Availability of pallet family f at the entrance of shop-floor (stochastic)

\tilde{T}_{scf} Processing time of station s in column c for family f (triangular fuzzy set)

Variables:

co_{jf} Completion time of product j in family f shop-floor, $\in R^+$

N_f Number of product j in each family f , $\in R^+$

Variables:

$X_{scjf} = 1$ if product j family f on station s in column c , 0 otherwise

W_{scjf} Waiting time of product j in family f before operation on station s in column c , $\in R^+$

R_{scjf} Release time of product j in family f on station s in column c , $\in R^+$

AM_{scjf} Availability time of station s in column c for product j in family f , $\in R^+$

C Total (weighted) completion times, $\in R^+$

Objective:

$$Min \text{ Av. TPT} = \sum_f \sum_j \left(\frac{(co_{jf} - e_{jf})}{N_f} \right) + \sum_f \sum_j (e_{jf} - r_{jf}) \quad (3.3.1)$$

s.t.

$$C = \sum_f \sum_j \alpha_f co_{jf} \quad (3.3.2)$$

$$C - \sum_s \sum_c \sum_j \sum_f (X_{scjf} [\tilde{T}_{scf} + W_{scjf}]) = 0 \quad (3.3.3)$$

$$r_{jf} = \max(\tilde{p}a_f, e_{jf}); \forall j, f \quad (3.3.4)$$

Binary decisions

$$X_{scjf} \in \{0,1\}; \forall s, c, j, f \quad (3.3.5)$$

$$\sum_s X_{scjf} = 1; \forall j, f, c \quad (3.3.6)$$

guarantees only one station in a column to be used

$$\sum_s X_{scjf} = \sum_s X_{s(c-1)jf}; \forall j, f, c; c > 1 \quad (3.3.7)$$

guarantees flow goes to next column

$$\sum_s \sum_{c=1}^1 X_{scjf} w_{scjf} = \max\left(\left(\sum_s \sum_{c=1}^1 X_{scjf} R_{scjf} - r_{jf}\right), 0\right); \forall j, f, c = 1 \quad (3.3.8)$$

waiting time in first column

$$\sum_s X_{scjf} w_{scjf} = \max\left(\left(\sum_s X_{scjf} Am_{scjf} - \left(\sum_s X_{s(c-1)jf} (R_{s(c-1)jf} + \tilde{T}_{s(c-1)f})\right)\right), 0\right); \forall j, f, c > 1 \quad (3.3.9)$$

waiting time for all columns bigger than one

$$\sum_{s=1}^3 X_{scjf} am_{scjf} \geq \sum_{h=1}^N \sum_{s=1}^3 (X_{schq} R_{schq} + X_{schq} \tilde{T}_{scq}); \forall f, c, j, q; f \neq q \quad (3.3.10)$$

guarantees the total release + processing time \leq availability of machine.

Sequencing constraints

$$R_{scjf} \geq R_{schf} + \tilde{T}_{scf} - M(1 - X_{scjhf}) \quad (3.3.11)$$

$$R_{schf} \geq R_{scjf} + \tilde{T}_{scf} - M(X_{scjhf}) \quad (3.3.12)$$

$$X_{scjhf} + X_{schjf} = 1; j \neq h \quad (3.3.13)$$

$$X_{scjhf} = 0; j = h \quad (3.3.14)$$

where the sequencing constraints guarantee no simultaneous processing happens in the same station.

5.3.2 Lpallets in Pull System

In addition to advantages of autonomy in macro scale by using hybrid systems, Conwip system gives a glorious benefit to pallets in shop floors. Since pallets are the means of Conwip control, they may learn the behavior of their working environment. As referred in [54], Conwip control, based on the constant work in process, has a limited number of cards or pallets for moving products. Those industries that use pallets, or alike, as pull signals give this opportunity to pallets to experience the situation of production lines and get up-to-date data in each round trip. In the previous sections, it was already explained that Conwip resembles closed-loops. In each cyclic round, pallets record some certain values for metrics in order to evaluate the performance of the system, lines, supply, and fulfillment operations.

Furthermore, for bearing learning ability to pallets, some fuzzy rules, as the controller, are adopted in order to judge and learn the behaviors. This is particularly applicable because of the uncertain nature of the supply, demand, and operation times. Although using fuzzy logic is not the only way of judging and learning, but it is one of the alternatives studied in this experiment. The exclusive fuzzy rules transmit decision variants that the pallets may confront with them. Lpallets, after carrying respective product(s), record all data about the time. It means they save important criteria, e.g., waiting time in a passed queue and its respective processing time in station, the code name of station, and the average time expended by pallets passed through this station. To some extent, these data are recorded in Lpallet as the source of knowledge and decision making. Then, based on some defined

fuzzy rules embedded in the controller, Lpallets make judgments for the past stations derived from linguistic (qualitative) inputs with membership values. These judgments are the foundation of later decision makings about routing selection.

After a while, cyclic flows through the lines and collecting experience, now an Lpallet, derived from its judgments, is able to select a route and proceed over it. This ability is achieved by two procedures as: judgment process and route selection. Although these procedures are not mutually exclusive in performance, they have two separate operating algorithms. The entire judgment process works based on the following algorithm:

| Algorithm of judgment process for Lpallets with fuzzy controller | |
|---|--|
| 1. Begin | |
| 2. If the operation in station is done then | |
| a. Reflect the waiting time and cycle time into fuzzy judgment operator | |
| b. begin | |
| i. fuzzify the crisp input value of waiting plus cycle time into membership value by the respective membership function | |
| ii. Judge this membership value of the queue and station by linguistic terms | |
| iii. Record this membership and linguistic judgment into the pallet | |
| c. end; | |
| 3. end; | |

Initially, different shapes of membership function are practiced for the fuzzy sets concerning linguistic judgments for experienced stations and queues. All of them are assumed to have flexible boundaries due to their moving average value. However, among all, the most reasonable one is the triangular function with variable space using the control chart with boundaries of [UCL LCL], inspired by statistical process control, see Haridy *et al.* [380]. Now, the fuzzification and linguistic judgment process for the specific [UCL LCL] is rendered based on its algorithm, as below:

| Algorithm of fuzzification for judgment process | | | |
|---|--|--|------------------|
| 1. Begin | | | |
| 2. $i = \text{experienced samples number}$ | | | |
| 3. $fa = \min_{1 \leq k \leq i} (x_k)$, $fb = \max_{1 \leq k \leq i} (x_k)$, $Rang = fb - fa$, | | | |
| 4. $avg = \bar{x} = \sum_{k=1}^{\text{sample}} \frac{x_k}{\text{sample}}$, $Med = \frac{fb-fa}{2}$, | | | |
| 5. $Aavg = \sum_{k=1}^i \frac{\bar{x}_k}{i}$, $ARang = \sum_{k=1}^i \frac{Rang_k}{i}$, | | | |
| 6. $UCL = Aavg + (E_E) \times ARang$, $LCL = \max(Aavg - (E_E) \times ARang, 0)$ | | | |
| 7. $E_E = 1.468$ | | | |
| 8. If $x < (Aavg)$ and $x > \frac{(LCL+Aavg)}{2}$ then | $\mu_e = \frac{x - \frac{(LCL+Aavg)}{2}}{Aavg - \frac{(LCL+Aavg)}{2}}$ | | is normal |
| 9. If $x < \frac{(UCL+Aavg)}{2}$ and $x > (Aavg)$ then | $\mu_e = \frac{\frac{(UCL+Aavg)}{2} - x}{\frac{(UCL+Aavg)}{2} - Aavg}$ | | is normal |
| 10. If $x > (Aavg)$ and $x \leq UCL$ then | $\mu_e = \frac{x - Aavg}{UCL - Aavg}$ | | is bad |
| 11. If $x < (Aavg)$ and $x \geq LCL$ then | $\mu_e = \frac{Aavg - x}{Aavg - LCL}$ | | is good |
| 12. If $x \geq UCL$ then | $\mu_e = 1$ | | is bad |
| 13. If $x < LCL$ then | $\mu_e = 1$ | | is good |

14. **end;**

In fact, there are two alternatives in the presence of vagueness for dispatching pallets to parallel stations. The first alternative is to rely on the imprecise linguistic terms about queues at the moment, called here (NoLP), and is not pertinent to the judgment process. These linguistic terms define the best station for dispatching, see following:

Algorithm of route selection, relying on linguistic terms of queues

1. **Begin**
 - a. **For** $i=1$ to number of successors
 - i. Check linguistic terms and membership value of queue (i)
 - ii. If the term is "Speedy" then has priority 1
 - iii. If the term is "Lowspeedy" then has priority 2
 - iv. If the term is "Nospeedy" then has priority 3
 - b. **Next;**
 - c. Take the maximum membership value in each priority
 - d. Choose the Queue with higher priority and membership value
2. **end;**

On the other hand, the second alternative is to use the Lpallets and employ their judgment ability, called (LP). After judgment of stations, in order to select the best parallel station out of three, the route selection algorithm is triggered. Here, an extension happens to both linguistic terms out of a current situation of queues and the recorded judgments (experiences) inside an Lpallet. Finally, the decision for dispatching is made by the extension principle of Zadeh [302], see following for its algorithm.

Algorithm of route selection, relying on linguistic terms of queues

1. **Begin**
2. **While** $i \leq$ number of successors do
 - a. **begin**
 - i. Check the linguistic term and its membership value of station (i)
 - ii. In Lpallet, check linguistic judgments and membership values of last three records about queue & station number (i)
 1. Take the min operator of the last three records in Lpallet, see table 3
 2. Take the max (OR) operator between this derived value of Lpallet and the membership value of linguistic judgment in station (i) (Zadeh extension, see FAM)
 3. Imply the membership values out of premise of respective fuzzy rule to the consequent by alpha cut method (truncation)
 4. Aggregate the consequent membership values by method sum
 5. Defuzzify the fuzzy values of consequences to crisp value for the successor
 - b. **end;**
3. **Next;**
4. Compare the crisp values of each successor and take the one with the least value as selected successor

5. (Call Judgment algorithm)

6. **end;**

Here, the Mamdani fuzzy inference system [381] [382] is applied. Besides, the defuzzification method is the weighted average [383] that its estimation algorithm is presented in following.

Algorithm of route selection, relying on linguistic terms of queues

1. **Begin**

a. $m_1 = \max$ (membership value of Good station, Speedy station)

b. $m_2 = \max$ (membership value of Normal station, Lowspeedy station)

c. $m_3 = \max$ (membership value of Bad station, Nospeedy station)

i. If $(m_1 \wedge m_2 \wedge m_3) \neq 0$ then

Crisp value of the respective queue & station =

$$\frac{[(a+(c-a) \times m_1) + (m_2 \times \frac{(d-b)}{2} + b) + (c+(e-c) \times m_3)]}{m_1 + m_2 + m_3}$$

ii. elseif $(m_1 \wedge m_2) \neq 0$ then

$$\text{Crisp value of the respective queue \& station} = \frac{[(a+(c-a) \times m_1) + (m_2 \times \frac{(d-b)}{2} + b)]}{m_1 + m_2}$$

iii. elseif $(m_1 \wedge m_3) \neq 0$ then

$$\text{Crisp value of the respective queue \& station} = \frac{[(a+(c-a) \times m_1) + (c+(e-c) \times m_3)]}{m_1 + m_3}$$

iv. elseif $(m_2 \wedge m_3) \neq 0$ then

$$\text{Crisp value of the respective queue \& station} = \frac{[(m_2 \times \frac{(d-b)}{2} + b) + (c+(e-c) \times m_3)]}{m_2 + m_3}$$

v. elseif $(m_1) \neq 0$ then

$$\text{Crisp value of the respective queue \& station} = \frac{[(a+(c-a) \times m_1)]}{m_1}$$

vi. elseif $(m_2) \neq 0$ then

$$\text{Crisp value of the respective queue \& station} = \frac{[(m_2 \times \frac{(d-b)}{2} + b)]}{m_2}$$

2. **end;**

Graphical representative of the fuzzy associative memory (FAM) for selection of successor station based on experienced judgments and current imprecise linguistic terms of successors is displayed in Figure 77.

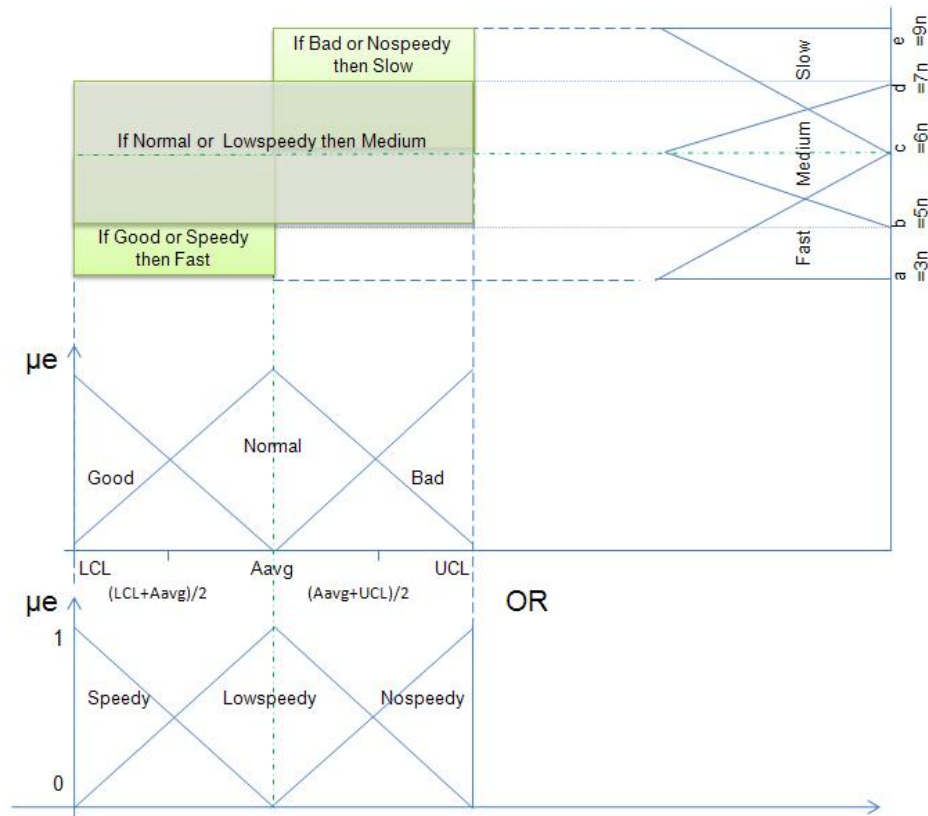


Figure 77: Applied fuzzy associative memory.

Table 13 presents the performance of fuzzy rules in the presence of queue linguistic terms, used in extension. Table 14 defines the FAM in case of *Min* operator for several records (experiences). In order to compare the performance of the stated LP method, some alternatives are used, e.g., QLE. However, for adopting uncertainty in processing time, the performance of QLE must be adjusted. This adjusted QLE is called (QLE.Fuzzy). The performance of the adjusted method is exactly the same as QLE but the processing time of every existing pallet in a queue is fuzzy configured (i.e., triangular). This method is applied in the experiment in the previous section.

Table 13: Performance of fuzzy rules with the presence of queue linguistic terms, using in extension.

| OR | Good | Normal | Bad |
|-----------|--------|--------|--------|
| Speedy | Fast | Fast | Medium |
| Lowspeedy | Fast | Medium | Slow |
| Nospeedy | Medium | Slow | Slow |

Table 14: Representation of fuzzy rules without presence of queue linguistic terms.

| AND | Good | Normal | Bad |
|--------|--------|--------|--------|
| Good | Fast | Fast | Medium |
| Normal | Fast | Medium | Slow |
| Bad | Medium | Slow | Slow |

5.3.3 Simulation Results Analysis

Several experiments are conducted for this study. Firstly, local throughput time (LTPT) of different control methods is compared, by one piece in pallets' lot size. Secondly, this is

experimented for alternative lot sizes in pallets. Thirdly, these states are compared with two flow alternatives as push and pull. Fourthly, LTPT and global TPT (GTPT) of the methods are compared against each other in the presence of stochastic breakdowns for all stations. This time, not only TPT of the methods, but utilization of stations, WIP, and the makespan of all 500 final products in each type, are given.

Choosing the inflow of the source plants as the Gamma pdf ($\alpha = 1.65, \beta = 1.57$) causes stochastic replenishments in OEM. The mixed average of inflows can be approximated best by the Gumbel max distribution ($\sigma = 1.09, \mu = 1.96$). At the same time, customers' orders come with neg-exponential pdf ($\lambda = \frac{1}{\beta} = 0.38$) as it is likely in practice. Condensed supply and demand rates compromises the influence of previous plants upon shortage in entrance inventory. Nonetheless, the fully stochastic system with random supply, demand, and operations, addresses a fully dynamic system with highly variable factors. Additionally, ambiguity in recognizing the exact state of buffers (queues) and stations in each event leads to imprecise decisions for choosing the best successors. Consequently, it results in higher GTPT for the general network, and higher LTPT in the OEM. However, in the first experiment, by considering vague data, application of Lpallets shows an improvement of (49 minutes) in overall average LTPT (ALTPT), see Figure 78.

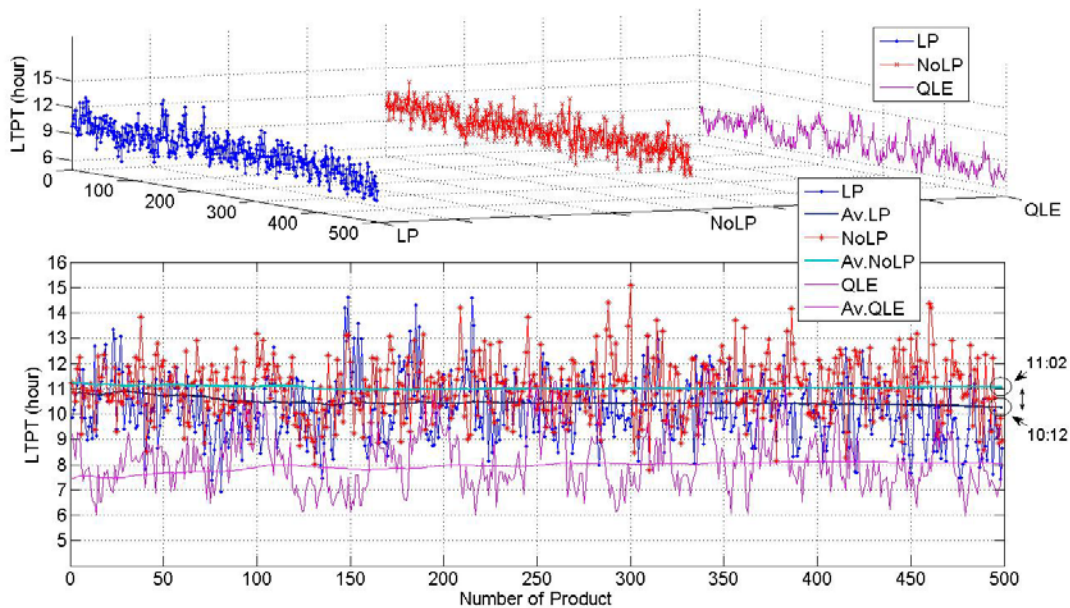


Figure 78: Comparison of LTPT for LP, NoLP, and QLE in first pdf circumstance.

In Figure 78, three alternatives are compared against each other; application of Lpallets with judgment capability (LP), without using Lpallets by just relying on the linguistic terms of parallel queues based on imprecise information of queues (NoLP), and the precise estimation of waiting time in each parallel queue and station based on real QLE. As it is obvious, the trend of ALTPT in Lpallet (Av.LP) is smoothly inclining towards 10 hours that reflects learning, while ALTPT in NoLpallet (Av.NoLP) constantly follows over 11 hours.

However, QLE is just covered for comparison and is not compatible with the assumed vagueness in the available data.

Furthermore, by changing the neg-exponential inflow of the sources to ($\beta = \frac{1}{\lambda} = 0.33$) the inflow stream to the OEM changes as well. In the same way, again the pdf of the mixed-average of all types supply is approximated by Gumbel Max distribution ($\sigma = 1.33, \mu = 2.36$), see Figure 79. For the single type product to OEM see appendix B. This proves that although changes in flow pdf of previous nodes have effects on the replenishment distribution in OEM, but its pdf generally stays similar. Simultaneously, the pdf of customer orders is changed to neg-exponential by $\lambda = \frac{1}{\beta} = 0.33$.

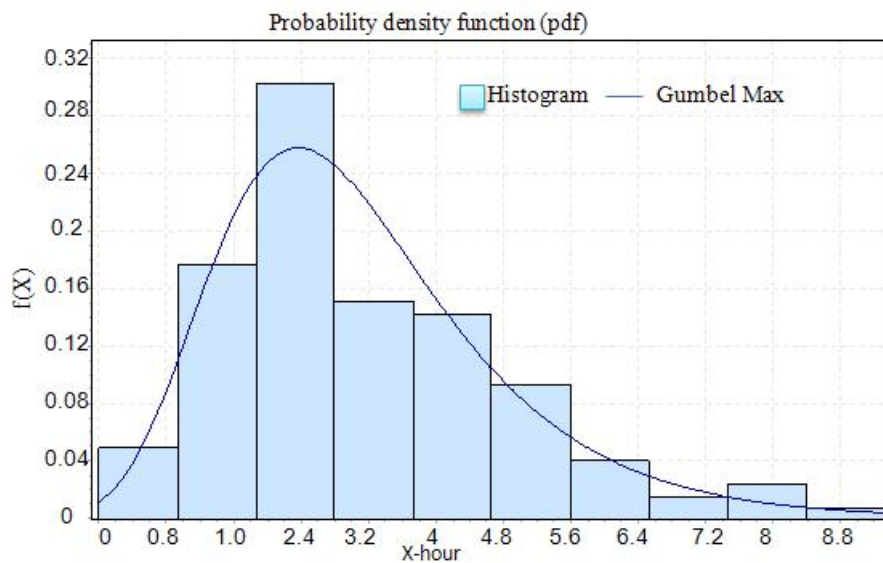


Figure 79: Probability density function of the average of all three types of products inflow in OEM.

These changes indicate a better sensitive analysis for the entire network as well as inside the emphasized plant. This time, not only one piece flow but the influence of different lot sizes of pallets is experimented. In this case, LP alternative has two variants: LP with constant lot size (LP-No-Va) and LP with flexible lot size (LP-Va). Regarding the learning ability, in lot sizes with more than one, Lpallets are able to reduce their lot size temporarily in the presence of congestions. This happens concerning the previous judgments for the first tier stations, i.e., if the judgment was bad then in this round Lpallet takes one piece less than the real lot size. Table 15 shows ALTPT in different alternatives with Conwip control.

Accordingly, the ratio of ALTPT of each control method to the average of all methods, in each lot size, is compared in Figure 80. Additionally, in order to compare the adopted pull strategy with material push, the ALTPT ratios of pull to push are displayed on Figure 81.

Table 15: ALTPT in different alternatives for Conwip flow control.

| | ALTPT (Hour) |
|--|--------------|
|--|--------------|

| | Lot=1 | Lot=2 | Lot=3 |
|-----------|-------|-------|-------|
| QLE | 7.19 | 15.52 | 23.62 |
| LLP-No-Va | 9.71 | 20.86 | 32.52 |
| LP-Va | 9.71 | 18.86 | 29.76 |
| No-LP | 10.49 | 22.17 | 33.66 |

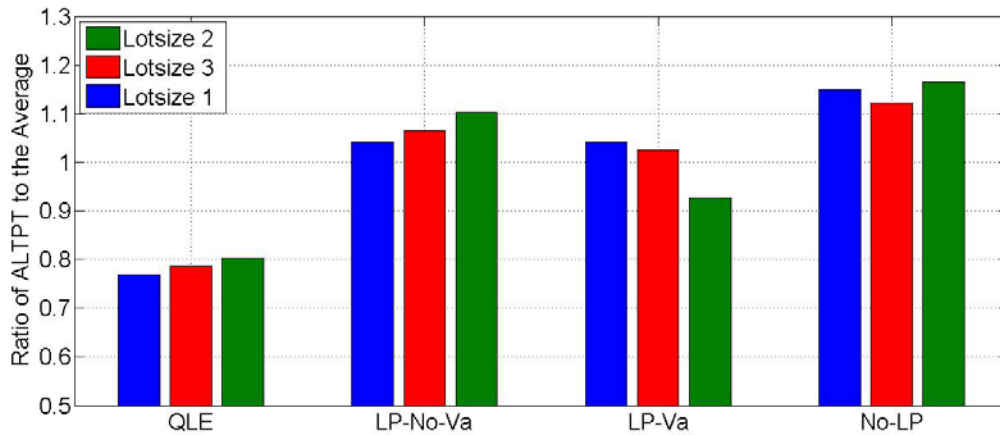


Figure 80: Ratio of ALTPT to average of all alternatives with different lot sizes.

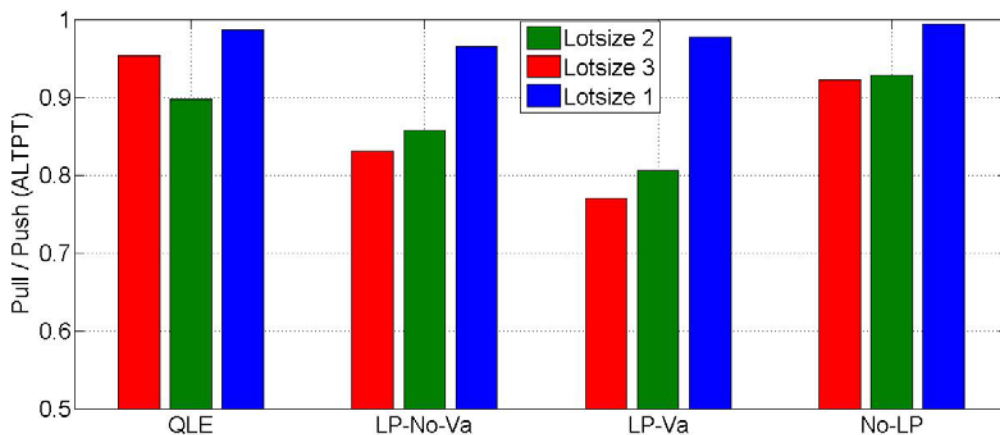


Figure 81: Ratio of ALTPT in pull to push for all alternatives with different lot sizes.

It is noticeable that although by using push system there is a short increase in the number of delivered products, but the LTPT increases by hours. This is because; the queue numbers sophisticatedly rise in the network. Eventually, higher LTPT less delivered products in a time frame. On the other hand, by increasing the intervals between two orders the rate of overproduction between interval times and simultaneously LTPT increases in push. Table 16 presents the ratio of ALTPT for each alternative to the average of all alternatives in the same lot control system. This happens by three different lot sizes and with push and pulls systems. It can be seen that one piece flow as an objective of lean manufacturing makes better results. Additionally, it shows that pull system has more consistency with LP method.

Table 16: Ratio of ALTPT for each alternative to the average of all alternatives in same lot control system.

| | ALTPT (Hour) | | | | | |
|------------------|---------------------|-------------|-------------|-------------|-------------|-------------|
| | Lot1 | | Lot2 | | Lot2 | |
| | Push | Pull | Push | Pull | Push | Pull |
| QLE | 0.77 | 0.77 | 0.78 | 0.80 | 0.71 | 0.79 |
| LLP-No-Va | 1.06 | 1.05 | 1.09 | 1.08 | 1.13 | 1.09 |
| LP-Va | 1.05 | 1.05 | 1.05 | 0.97 | 1.11 | 0.99 |
| No-LP | 1.11 | 1.13 | 1.07 | 1.14 | 1.05 | 1.13 |

Obviously, fewer incoming orders' rate more discrepancy between push LTPT and pull LTPT is expected. Note that GTPT of the entire batch (500 products of each type) in push system shows a fall in comparison to pull Conwip. This is because the entrance inventory may be eliminated or reduced, which affect the waiting time there. While the lead time of assembling semi-finished products to finished products is removed in push, the finished product inventory may increase dramatically. Therefore, these may cause a decrease in GTPT whereas the autonomy of a single plant can be beat by push material, since there is no self-control on both inventories. Furthermore, by considering breakdowns for stations, the LP scenario reflects again a positive performance in comparison with the other cases as QLE and NoLP. Here, in addition to the conventional performance of QLE with precise estimation of queues' waiting times, fuzzy system is included in the estimation process of QLE in order to take uncertainty into consideration. Figure 82 presents the alternative methods without breakdowns, while Figure 83 depicts the same alternatives under breakdown circumstance.

However, in the both figures the best emerged operating method is QLE with fuzzy capability (QLE.Fuzzy). The stations' availabilities are 80% for stations in column 1, 90% for column 2, and 80% for stations in column 3 that each mean repair time (MRT) is assumed to be one day. Nonetheless, the best performing method in the previous experiments was (QLE) that by considering breakdowns presents the worst case. In Fig. 14, the LTPT of the introduced methods are illustrated. Here, the standard deviation of LP =11:33 hour, NoLP =14:20 hour, QLE =15:01 hour, and QLE.Fuzzy =8:23 hour. This reveals a more stable performance for LP in the absence of QLE.Fuzzy case.

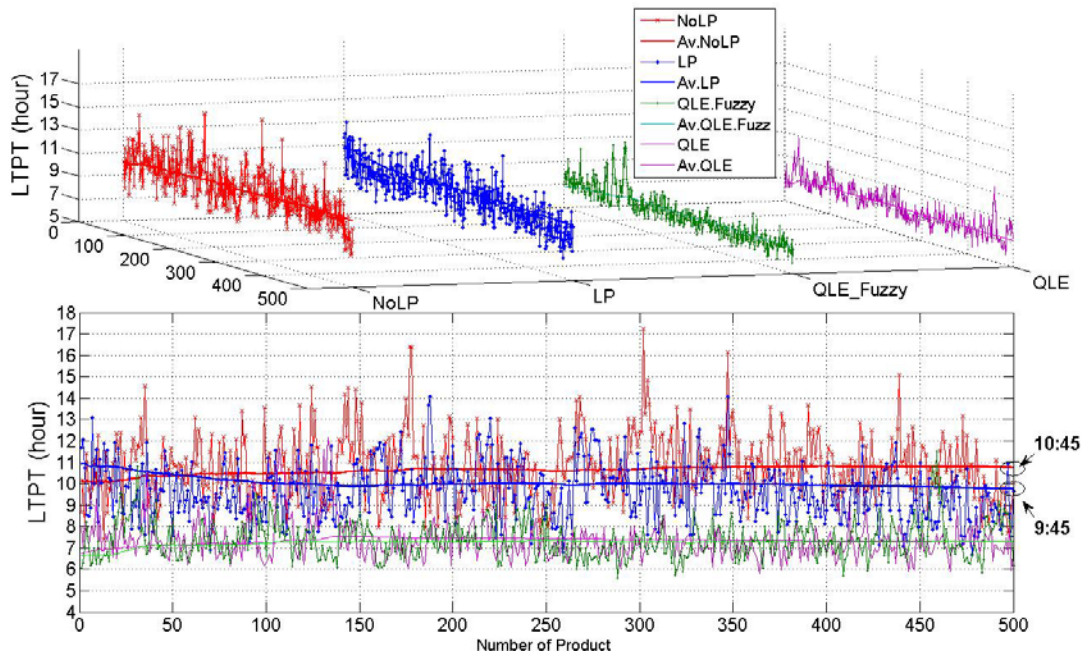


Figure 82: Comparison of LTPT for LP, NoLP, QLE.Fuzzy, and QLE in second pdf circumstance.

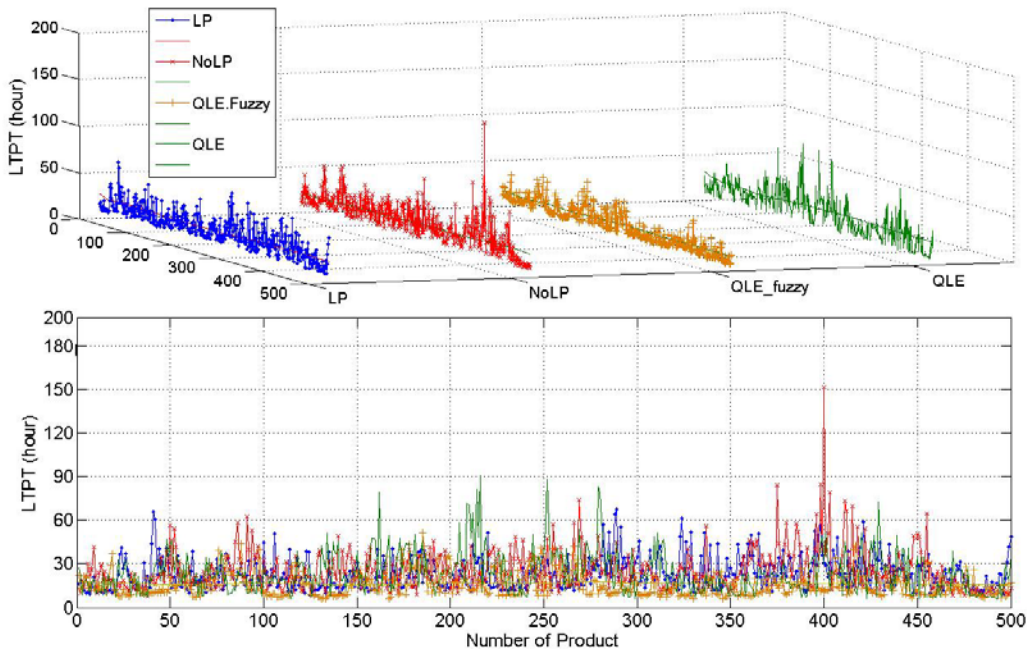


Figure 83: Comparison of alternatives with breakdowns in second pdf circumstance.

For all experiments, so far the number of available pallets for each type of product was considered constant, as six. Nevertheless, by increasing the number of pallets (No. of Pallet), the ALTPT and AGTPT change. This is caused by the rise in queue lengths of stations as well as the decrease in entrance inventory. The comparison of ALTPT between current control methods in alternating the number of pallets is shown in Figure 84. At the same time, the trend of AGTPT for the similar comparison is given in Figure 85.

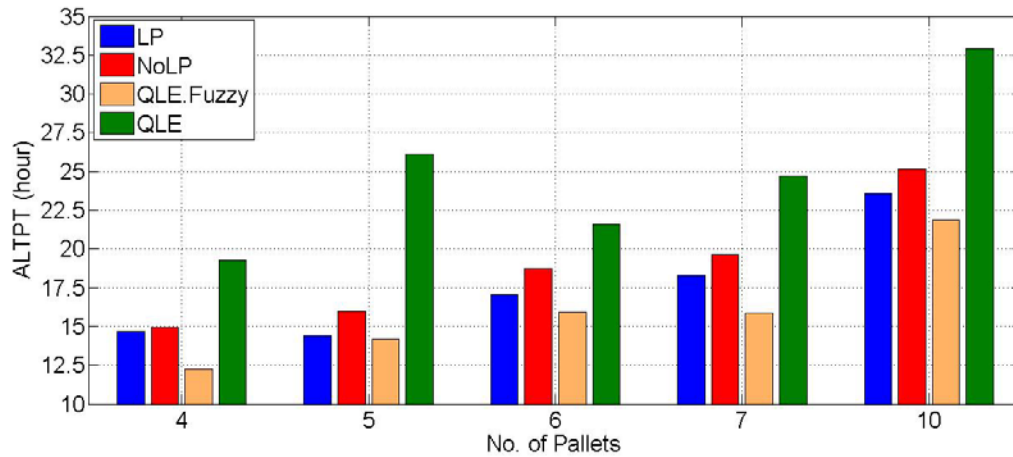


Figure 84: ALTPT in presence of different No. of Pallets, for all alternatives.

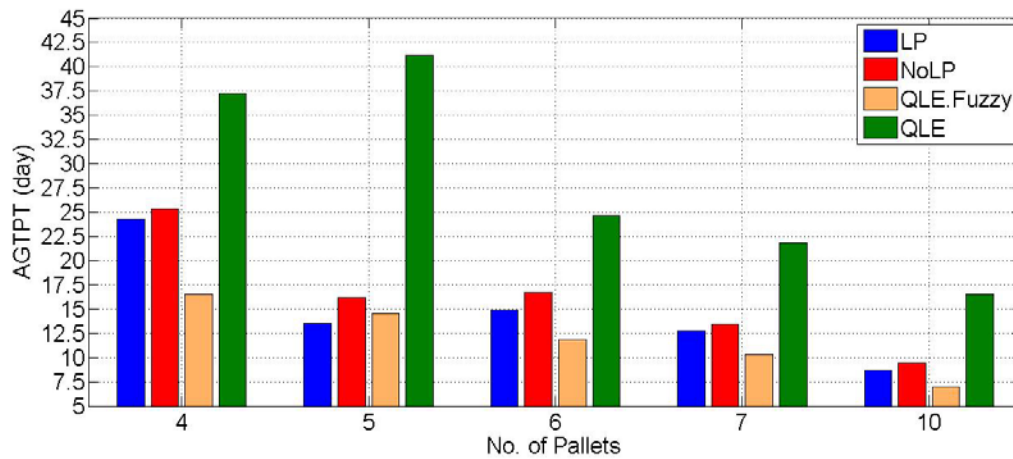


Figure 85: AGTPT in presence of different No. of Pallets, for all alternatives.

By compromising the behaviors of ALTPT and AGTPT it can be concluded that in LP method the best performing No. of Pallet equals to 5. This shows a tradeoff between different decision factors, this was experimented in last section. In addition, Table 17 reflects the performance of all methods with different No. of Pallets in numerical experiments.

Table 17: Numerical experiments in alternative No. of Pallets and control method in Conwip with breakdowns.

| Nopallets | 4 | | | | |
|------------------|--------------|-------------|---------------------|-----|------------------|
| Control Strategy | ALTPT (hour) | AGTPT (day) | Makespan (day:hour) | WIP | A_Utilizati on % |
| LP | 14.69 | 24.31 | 115:09 | 606 | 55.88 |
| NoLP | 14.94 | 25.30 | 116:14 | 626 | 55.86 |
| QLE_Fuzzy | 12.22 | 16.51 | 102:03 | 467 | 58.50 |
| QLE_noFuzzy | 19.28 | 37.29 | 142:05 | 750 | 41.27 |
| Nopallets | 5 | | | | |
| LP | 14.38 | 13.51 | 98:15 | 409 | 62.53 |
| NoLP | 15.96 | 16.17 | 99:14 | 428 | 65.02 |
| QLE_Fuzzy | 14.19 | 14.53 | 96:13 | 351 | 63.18 |
| QLE_noFuzzy | 26.14 | 41.14 | 147:12 | 856 | 41.07 |
| Nopallets | 6 | | | | |

| | | | | | |
|--------------------|-----------|-------|--------|-----|-------|
| LP | 17.04 | 14.90 | 97:00 | 383 | 65.37 |
| NoLP | 18.74 | 16.70 | 97:03 | 392 | 67.93 |
| QLE_Fuzzy | 15.91 | 11.87 | 93:21 | 342 | 65.33 |
| QLE_noFuzzy | 21.59 | 24.67 | 114:03 | 583 | 52.59 |
| Nopallets | 7 | | | | |
| LP | 18.29 | 12.70 | 91:01 | 288 | 70.16 |
| NoLP | 19.66 | 13.41 | 93:23 | 296 | 67.26 |
| QLE_Fuzzy | 15.87 | 10.31 | 84:12 | 190 | 70.99 |
| QLE_noFuzzy | 24.69 | 21.79 | 109:10 | 612 | 55.61 |
| Nopallets | 10 | | | | |
| LP | 23.57 | 8.71 | 86:09 | 167 | 74.24 |
| NoLP | 25.14 | 9.44 | 85:13 | 258 | 75.93 |
| QLE_Fuzzy | 21.86 | 6.94 | 83:01 | 108 | 75.37 |
| QLE_noFuzzy | 32.90 | 16.57 | 102:06 | 426 | 59.63 |

In order to verify the performance of our simulation model in general, a flexible flow shop scheduling problem with conventional characteristics is considered to be solved classically, i.e., no breakdowns, 48 jobs to be processed (16 each type), normal processing times, neg-exponential release times $\beta = 2$ hour, and offline manner. Table 18 compares the completion times (Cmax) of our simulation methods and the classical solutions for scheduling, using dispatching rules, i.e., shortest processing time (SPT) and longest processing time (LPT), first come first serve (FCFS), and general shifting bottlenecks routine (GSBR). The free version of LENKIN scheduling system is utilized to operate the scheduling, thus the number of jobs is limited here. However, it should be mentioned that such limited jobs may not cover a proper learning phase. Additionally, in classical solutions global information about the problem (e.g., all jobs, release and due dates) must be available as well as no constraints can be assumed in terms of carries number and pull approach. Nonetheless, in the current study with its individual approach no general information is required.

Table 18: Comparison of simulation methods with classical scheduling algorithms.

| | Scheduling Methods Makespan (minute) | | | | | | |
|---------------------------------|---|------------|-------------|-------------|-----------|-------------|------------------|
| | SPT | LPT | FCFS | GSBR | LP | NoLP | QLE.Fuzzy |
| $\beta = 120$ | 3890 | 3890 | 3890 | 3890 | 3336 | 3653 | 3140 |
| $\beta = 90$ | 2756 | 3364 | 2622 | 2610 | 3248 | 3483 | 3338 |

5.3.4 Experiment Summary

This experiment was generally divided into two parts as conceptual and experimental. In the first part after a short introduction, a general concept about material flow control systems was explained. Later, to clarify the basis of Lpallet concept, an introduction was given to closed-loop systems and respective privileges for learning. Afterwards, application of Lpallets in logistics was described. In order to enter into the second part, a practice oriented scenario was presented for the advantages of using Lpallets in Conwip control. The mathematical representation of the considered problem was given respectively. Following them, the employed fuzzy sets to control the Lpallets were explained in details. At the end, the simulation results of the scenario under different circumstances were

analyzed, and the assumptions in the simulation were compared together by means graphs. In analyzing the performance of Lpallets (LP) under several conditions, its superiority than other methods is perceived, although its advantage was proportional. Together with evaluating LP some other effective factors in logistics were presented here. For instance, there was compared the performances of push material vs. pull material, the role of the number of carriers (pallets) in congesting the queues, makespan, and utilization. Eventually, the difference between ambiguous and exact information was given in NoLP and QLE methods. Additionally, it was shown that despite knowing the exact number of pallets in queues, facing uncertainty, the sole QLE does not work properly, while the considering fuzzy numbers (QLE.fuzzy) outperform all other methods. However, the purpose of this experiment is to show the usability of LPallets with the availability of vague information. Conclusively, in this experiment, just a learning methodology (i.e., the fuzzy controller) was exploited that showed some advantages to the learning entities (Lpallets) as well as the entire system. Here, no direct error is taken into account and no direct negotiation happens to autonomous entities, which may enhance the merit of adaptability. Nevertheless, the learning methodology can be equipped with more intelligent methodologies. As further works, there are some requirements in terms of fuzzy domain classification and precision in mapping inputs into outputs by considering feedback errors. This performance can be improved with the assistance of neural networks. In addition, some evolutionary techniques can be applied to avoid local traps in generating new combinations of variables and learning; besides, it may be used for experimenting new decisions. A suitable evolutionary technique is GA and its related features like genetic programming. Application of these evolutionary techniques and neuro-fuzzy methods for learning and controlling Lpallet is the subject of future works for the authors.

5.4 Application of Learning Pallets in Hybrid Flow-Open Shop Scheduling, Using Artificial Intelligence

This experiment is directly inspired by a prototype of an assembly production line placed in the lab of BIBA Institute at Bremen University for the purpose of autonomous control experiments, see Figure 86. The same scenario is modeled by simulation with the intension of purely evaluating the performance of Lpallets in real-time scheduling and control decisions. The results have been shown that Lpallets can adequately deal with a fully dynamic assembly line without any information about the situation of semi-finished products' replenishment time and number of orders as well as the condition of machines in terms of queues. The goal of this experiment is to evaluate whether Lpallets can enhance and simplify real-time scheduling and control tasks in inbound logistics. This section is based on the conference paper by Mehraei and Scholz-Reiter [176], presented at 44th CIRP conference at Madison University.

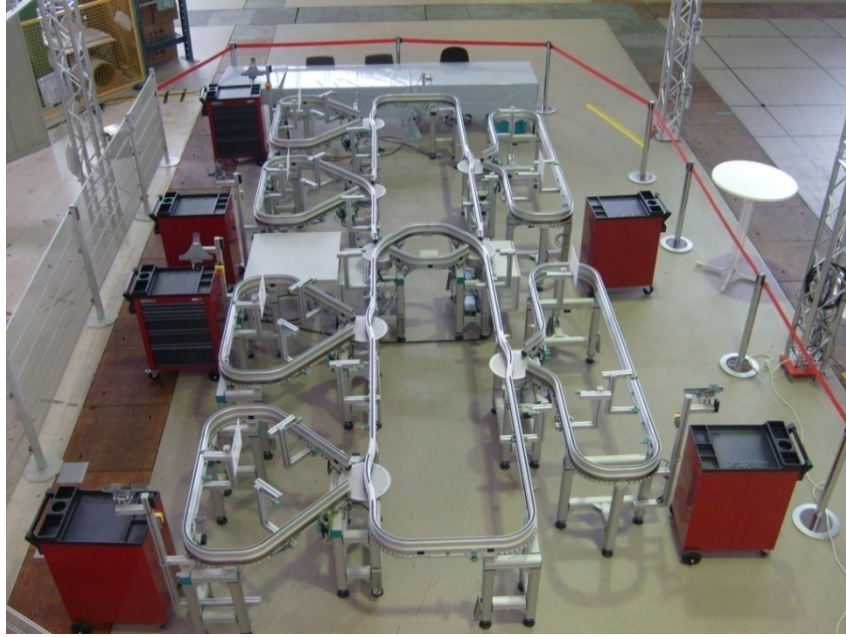


Figure 86: The prototype of assembly line located in the lab of BIBA Institute.

5.4.1 Hybrid Flow-Open Shop Problem

In flow shop problem each job j requires to be processed on all m machines in series. In other words, all jobs have to follow the same route, i.e., each job is processed with the similar order on each machine and the operations for each job is equal to m . If all machines follow FIFO rule then the problem is called *permutation flow shop* scheduling (Per_Flow). However, there are some other variants defined for this problem. In case of open shop, each job j has to be processed by each machine with processing times that some of which may be zero. In open shop, there is no restriction in terms of operations' orders, i.e., each job can have its own route and different jobs can have different orders (routes). However, if a job j has some operations to be done on all machines this resembles a hybrid flow-open shop problem if following condition holds true. If some of the operations have alternative permutations, while other operations must be done in order, this is called a hybrid flow-open shop. This analogy is used to explain our problem in this experiment.

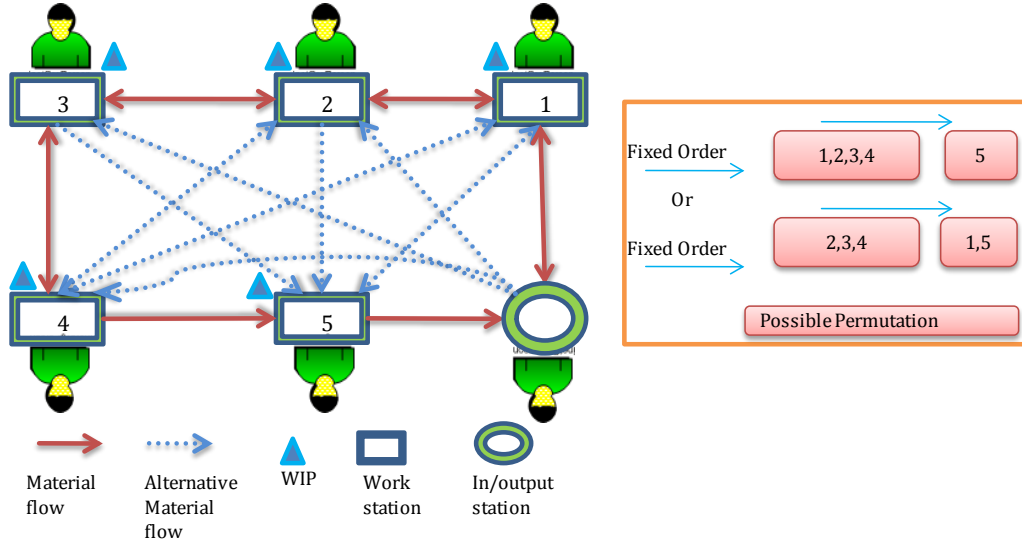


Figure 87: Possible permutations in operations order for the current experiment scenario and possible permutations in operations order (sequence).

5.4.2 Assembly Scenario

Generally, five (5) working stations are assumed for the assembly line with one (un)load station, see Figure 87. Three (3) final product types are imagined for delivery. Number of operations O_{jm} of a job j is equal to the machines' number m , so that each operation is for specific machine. Therefore, each operation has the same number as machines, i.e., 1, 2,..., 5. Although incoming jobs have freedom in selecting the operations from number 1 to 4, but there is a fixed constraint in the last machine. It means the last operation must be number 5 or 1, because of design restrictions. In addition, if the last operation is number 1, then the previous operation of that must be done on machine 5, see Figure 87.

With regard to the probability fact of $P(A \cup B) = P(A) + P(B) - P(A \cap B)$, this specific constraint results in $(4! \times 1! + 3! \times 2! - 3!) = 30$ possibilities for allocating jobs' operations to the m machines. However, without any restriction the number of permutation with respect to the combination of $\binom{S+K-1}{S-1}$, where S defines the number of station and K denotes product types, would result in $7!/(4! \times (7-4)!) = 35$.

Nonetheless, the distributed structure of this problem in terms of machines and pallets besides the stochastic nature of all processes make this allocation problem a case of complex real-time scheduling over the time horizon. With this highly dynamic system in practice, all arrival times of incoming jobs to the assembly line are not fixed in advance. In other words, the supply rate of incoming jobs is stochastic and their intervals follow neg-exponential distribution with $\beta = 50$ min. Each station has its processing time for each type of product. Table 19 shows the processing time for each product type on each machine plus setup time occurs in exchange of product types. Obviously, the line is not balanced as is expected in conventional pull systems. Finally, there is a batch of products, i.e., 150 final products in each type, to be assembled in this line.

Table 19: Processing times on each station.

| PROCESSING TIME FOR STATIONS | | |
|------------------------------|--------------------|------------------|
| Station | Process time (min) | Setup time (min) |
| 1 | 15 | 5 |
| 2 | 10 | 5 |
| 3 | 17.5 | 5 |
| 4 | 10 | 5 |
| 5 | 17.5 | 5 |

However, in real-world, the semi-finished products replenished externally, are moved through stations by means of pallets (or fixtures). Here, each product type has its respective pallet type, and all types have the equal number. The pallets have the duty of carrying semi-finished products from the entrance inventory, moving them through stations, and delivering them to the exit stock. The pallets stay there till the next corresponding semi-finished products comes to the entrance to redoing the same task. This is inspired by a Conwip that implies just a certain number of pallets circulating in the system. Additionally, if the product is available but the pallet is not ready, then the product must wait and it increases the makespan. Therefore, the pallets have iterative tasks to carry products over the scheduling horizon (assembly time) [261]. Moreover, it is noticeable that pull principle systems have originally decentralized control on material flow, which is pertinent to the notion of autonomous control, see Gurgur *et al.* [384] [385].

5.4.3 Lpallets in the Scenario

In the study, inspired by AI and the closed-loop routing pallets in Conwip, the concept of Lpallets is developed. It is assumed that pallets in each round trip can experience and learn the behavior of the local stations as well as the entire system. The GA and fuzzy logic techniques are separately integrated to Lpallets in order to find the best operation sequence for each pallet in each respective moment. This happens with regard to the experiments done by the pallet in the past. In addition, it is tried to combine fuzzy logic with ANN to improve its performance. Furthermore, Lpallets are able to make decentralized real-time decisions at each epoch (after triggered order), while defining the operations' orders for themselves. The best order in each moment tends to minimize the so far flow time F_j . However, the general multi-objective of this problem is following:

$$\left. \begin{array}{l} \text{Min } \sum_{j1=1}^{n1} \frac{F_{j1}}{n1} + \sum_{j2=1}^{n2} \frac{F_{j2}}{n2} + \sum_{j3=1}^{n3} \frac{F_{j3}}{n3} \\ \text{Min } \sum_{s=1}^5 \frac{Se_s}{n1+n2+n3} \\ \text{Min } C_{max} \\ \text{Max } \sum_{s=1}^5 U_s \end{array} \right\} \quad (3.4.1)$$

where s denotes the stations number, $n1$, $n2$, and $n3$ define the number of products in type 1, 2, and 3, respectively. All in all, the makespan C_m (completion time of the last product), flow time, average setup time Se should be minimized as well as overall utilization of stations U have to be maximized.

5.4.4 Application of GA

In this case, each Lpallet randomly generates 5 individuals (representing operations orders) out of 30 possibilities, as the first generation. Afterwards, in 5 time releases, the Lpallet examines all of the 5 individuals. Regarding the minimization objective ($Min F_j$), considered as Fitness function. At the end of each round (at un-load station) the fitness value of every round is calculated. When all individuals in a generation have fitness values (f_i), by using the roulette-wheel, the selection probability of each parent for mutation and crossover can be achieved. The mutation and the crossover rates are 0.02 and 0.8, respectively. In crossover, the selected parents mate by each other, so that two places of genes out of five (each representing an operation) in each parent are exchanged, according to the same operation place in the other parent. Figure 88 shows the crossover operation in the problem. The mutation happens to children randomly.

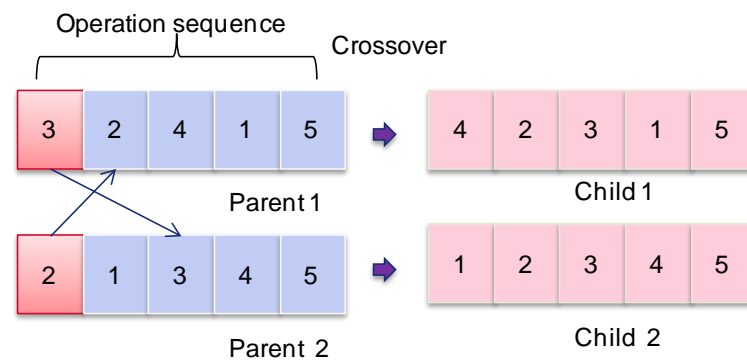


Figure 88: Crossover in the used GA.

This evolution procedure in generations holds on till no change happens to the operations' sequence (order) in new generations. This evolution procedure is always triggered again once any dynamics happens to the steady state of the assembly system. Although this model has individual Lpallets blindly operated—careless of other Lpallets—simultaneously the flow time in the end of each round reflects some characteristics of the current operating system in general, inspired by others' performances.

5.4.5 Application of Fuzzy Inference System

By integrating fuzzy controller (system) into Lpallets, each of which has the capability of estimating every station separately and judging them based on their current situation. These judgments are the decision criteria in the next rounds to define operations' sequence for each Lpallet. Similarly, this judgment technique is the same as the fuzzy system in the previous section, however, with small differences as follows.

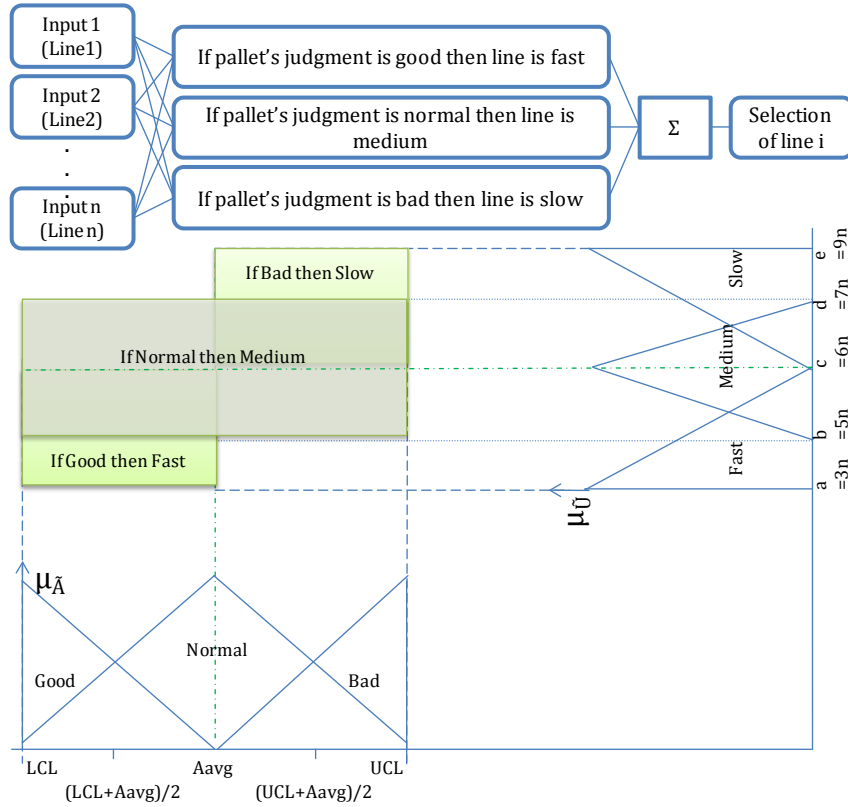


Figure 89: The applied FAM.

It is supposed that the waiting time in the queue of a station plus the processing time results in vague performance estimation in the respective station. Now, this criterion, as input of fuzzy system, is judged by three linguistic terms as: good, normal, and bad. Then, by means of alpha-cut technique, the membership values of these fuzzy linguistic terms are mapped into some other fuzzy terms (as fast, medium, slow) in the conclusion of the predefined rules. Afterwards, the judgments of stations accompanied with their associative membership values ($\mu_{\bar{U}}$) are recorded in $L_{pallets}$. Later in every decision era, these fuzzy values are defuzzified to a crisp value for every station. It means, in the entrance of each station, the fuzzy controller is triggered and compares the defuzzified (crisp) values of all left operations and will select the operation with the best crisp value (the least one), as the first operation. This sequence is achieved in descending order. These all happens via the corresponding fuzzy associative memory (FAM). Figure 89 displays the FAM used for this problem.

5.5 Application of Radial Basis Function Network

In this experiment, the considered ANN is RBF network (RBFN). This type of ANN is a two layer neural network with (usually) Gaussian transfer functions in the layer one (hidden) and sigmoid or linear functions in the second layer (output), to aggregate the outputs of the first layer. This type of neural network has a quicker training phase in comparison with other feed-forward networks [324]. For each station, there is an input vector, presenting the waiting time plus operating time of that station. In this experiment just three neurons are considered in the hidden layer, to represent the dependency strength of inputs to each

linguistic term as *good* (G), *normal* (N), and *bad* (B). In the second layer the linear function outputs a crisp value revealing the performance of that station, see Figure 90. This crisp value for each station is the criterion for sequencing the operations of assembly.

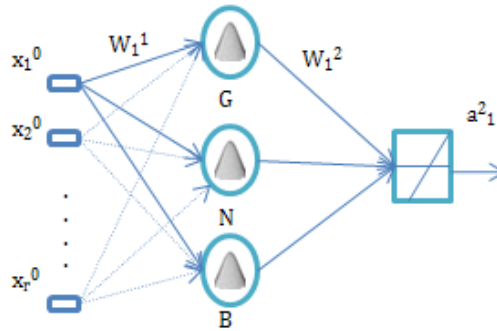


Figure 90: Topology of the applied RBF network for the experiment.

Moreover, it is assumed that there is no initial data for training the network. So, the training happens through the simulation run and in iterative routes of Lpallets between stations. With respect to the real-time training condition, one of the best training algorithms for this network is backpropagation with the steepest descent that is used by each Lpallet, for more information see ANN section. However, in this experiment each station has its own network embedded in Lpallets. In other words, the weights and kern vectors (centers of RBF) in hidden layer are specific for each station and the output of the network is just authentic for the respective station. Additionally, the training in this experiment is half-training just for defining up-to-date weights with regard to the current situation of a station.

Furthermore, the mechanism of the RBFN is inspired by the mechanism of the fuzzy controller in this experiment. Therefore, each new input from a station is treated like a fuzzy number and is tried to be fitted to one of the linguistic terms, represented by three RBFs in the hidden layer. In initial rounds of training the worst performance is considered as the kern vector of (B) of RBF, the best performance is placed in the kern of (G), and the kern of (N) is considered as the mid-point of the two others. However, in this experiment, the spreads (σ) of all functions are equal and are calculated by the distance of the G kern and B kern divided by 6. And the learning speed is selected as $\alpha = 0.2$.

5.5.1 Simulation Results

After examining several combinations of possibilities, the following results are achieved. The first examined variant is 15 pallets (5 each type), 150 product each type in batch, and the supply rate is neg-exponential with $\beta = 1/\mu = 50min$. The second variant is 12 pallets (4 each type), 150 product each type, supply rate is constant with 50 min inter-arrival time (rate=0.02). Table 20 exhibits the numerical experiments for the two variants and each method.

Table 20: Numerical experiments for each method for all three products as flow times and makespan.

| NUMERICAL PERFORMANCE OF METHODS (IN TIME) | |
|--|--|
|--|--|

| Method | Mean Flow,Type1 | | Mean Flow,Type2 | | Mean Flow,Type3 | | Makespan | |
|-----------|-----------------|------|-----------------|------|-----------------|------|-------------|-------------|
| | Variant | | | | | | | |
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Per_Flow | 6:01 | 4:44 | 6:01 | 4:56 | 6:00 | 4:58 | 7days+18:14 | 7days+22:35 |
| Fuzzy | 5:46 | 4:28 | 5:44 | 4:26 | 5:45 | 4:16 | 7days+ 9:23 | 7days+3:00 |
| Genetic | 5:47 | 4:44 | 5:47 | 4:41 | 5:43 | 4:45 | 7days+9:18 | 7days+12:40 |
| RBN+Fuzzy | 5:39 | 4:37 | 5:43 | 4:41 | 4:49 | 4:34 | 7days+6:00 | 7days+10:53 |

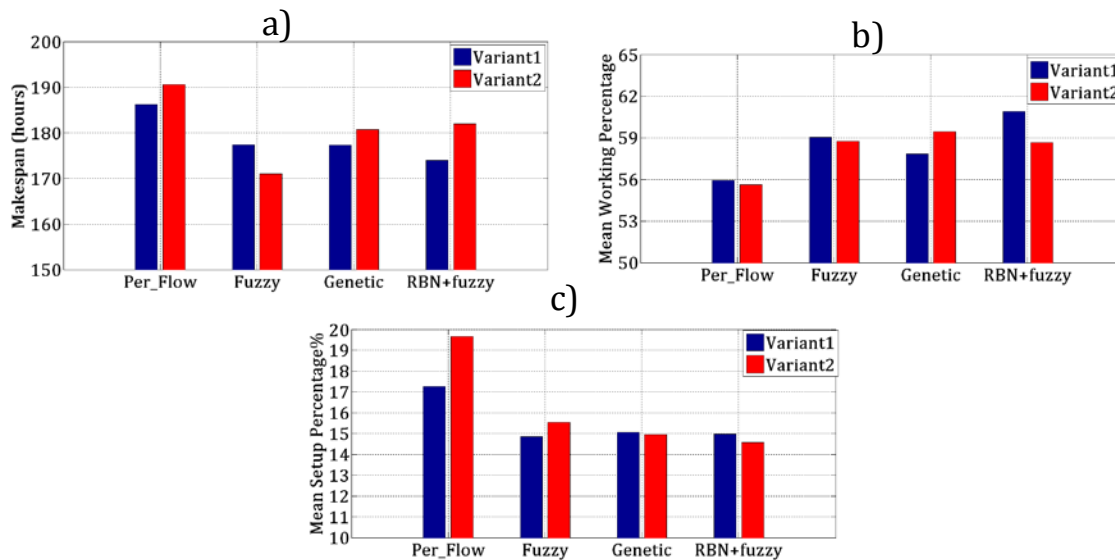


Figure 91: a) Makespan in every method, b) Stations working percentage in every method, c) Stations setup percentage in every method.

Figure 91a depicts the makespan of each AI method in the two variants. The utilization factor for each station is displayed by mean value of all stations' working percentage and setup percentage in Figure 91b and Figure 91c, respectively. However, there are some performances that the Per_Flow is the best schedule, e.g., if the incoming products' interval is constant, no setup time is required, and the processing time is not stochastic, then Per_Flow is the best choice.

5.5.2 Analysis by Closed Queuing Network

This section presents the application and suitability of closed queuing network theory in the sensitivity analysis as well as prediction of such closed-loop assembly systems. This is specifically important for checking the authenticity of Lpallets' decisions in real-time, in addition to the comparisons with conventional dispatching rules. In fact, queuing theory is recognized as a competent technique to model and analyze manufacturing networks and production lines. Thus, this theory is selected to reflect plausibility of Lpallets in the selected method with fuzzy controller system. This section is based on the paper by Mehraei *et al.* [175] published by IEEE explore. The equations and explanations about queuing theory and closed queuing network are avoided here but for more information see the section of queuing theory.

Basically, the queuing theory may be used to analyze those systems that work based on certain characteristics of this theory. In general, a system that consists of server(s) and customers with specific service and arrival rates, and a network of queues are the relevant subject for this theory. Here, since the number of pallets is fixed and the pallets just carry new arriving products through the stations in a cyclic manner, the entire system resembles a closed network with certain jobs and types. The key point is that the incoming products can just change the class of the jobs (Lpallets) and not the jobs' nature. Consequently, different sensitivity analysis can be exerted to this scenario by use of queuing network theory. The best queuing network model that fits best to the current scenario is called BCMP networks [386]. The BCMP networks consider a finite number of jobs with different types (classes) moving in a closed network with equilibrium [387]. However, some provided algorithm for analyzing closed networks are Marie, extended product form (EPF), and mean value analysis (MVA) [388] [389]. Accordingly, the most pertinent algorithm to the current problem is MVA that analyzes this network [390].

Furthermore, the specialty of the BCMP model by considering job classes and transition of them from one to another, by changing stations, represents different types of products in our problem. $P_{i,r,j,s}$ denotes the probability, that a class r job after receiving its service at station i changes to class s and requires service at station j . The network can be characterized by the following equations (3.4.2), (3.4.3), (3.4.4), which in certain iterations can be achieved. The size of iteration covers all possibilities of $\underline{k} = k_1, k_2, \dots, k_R$, so that k_r is the number of available jobs in class r in the network. Each k_r must span from zero to the existing number of jobs in that class. The iteration for solving such a network may require a large calculation memory and time. The visiting frequencies in all classes and all stations are calculated by solving the linear system (3.4.5).

$$V_i(k) = \tau_{ir} \left(1 + \sum_{r=1}^R L_{ir}(\underline{k} - b_r) \right); \forall i \in N, \forall r \in R \quad (3.4.2)$$

$$\lambda_r(\underline{k}) = \frac{k_r}{\sum_{i=1}^N V_{ir}(\underline{k})}; \forall r \in R \quad (3.4.3)$$

$$L_{ir}(\underline{k}) = \lambda_r(\underline{k}) \cdot V_{ir}(k); \forall i \in N, \forall r \in R \quad (3.4.4)$$

$$\left. \begin{aligned} e_{r1} &= e_{r1}p_{r1,r1} + e_{r2}p_{r2,r1} + e_{r3}p_{r3,r1} \\ &\quad + e_{r4}p_{r4,r1} + e_{r5}p_{r5,r1} + e_{r6}p_{r6,r1} = 1 \\ e_{r2} &= e_{r1}p_{r1,r2} + e_{r3}p_{r3,r2} + e_{r4}p_{r4,r2} + e_{r6}p_{r6,r2} \\ e_{r3} &= e_{r1}p_{r1,r3} + e_{r2}p_{r2,r3} + e_{r4}p_{r4,r3} + e_{r6}p_{r6,r3} \\ e_{r4} &= e_{r1}p_{r1,r4} + e_{r2}p_{r2,r4} + e_{r3}p_{r3,r4} + e_{r6}p_{r6,r4} \\ e_{r5} &= e_{r1}p_{r1,r5} + e_{r2}p_{r2,r5} + e_{r3}p_{r3,r5} + e_{r4}p_{r4,r5} + e_{r6}p_{r6,r5} \\ e_{r6} &= e_{r1}p_{r1,r6} + e_{r5}p_{r5,r6} \end{aligned} \right\} \forall r \in R \quad (3.4.5)$$

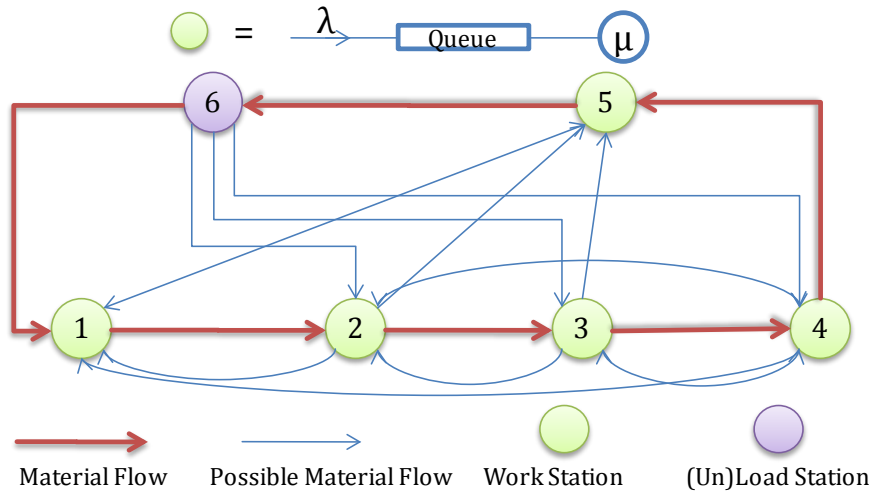


Figure 92: Closed loop assembly system (queuing network).

Indeed, in order to assimilate the current assembly problem to a real closed queuing network the (un)load station has to be considered as the sixth station in the network, see Figure 92. However, in order to solve the problem, an available software package called “WinPEPSY” is employed to solve the closed queuing network. Moreover, the simulation results from plant simulation software are quite comparable with the results out of WinPEPSY. The assumptions for the queuing model consist of $R = 3$, $K = 15$ (5 in each class), $N = 6$, i.e., the (un)load station in the closed network is considered as a station with its average service time, which explains the average waiting time of Lpallets in this station from unloading time to loading the next incoming product. However, in this experiment, the processing times in stations are different from the previous experiment. The mean service times (β), as neg-exponential, for all types of products are equal in the same stations. However, mean service times for all 6 stations are $\beta_1 = 30min, \beta_2 = 20 min, \beta_3 = 35 min, \beta_4 = 20 min, \beta_5 = 35 min, \beta_6 = 0.5 min$, respectively.

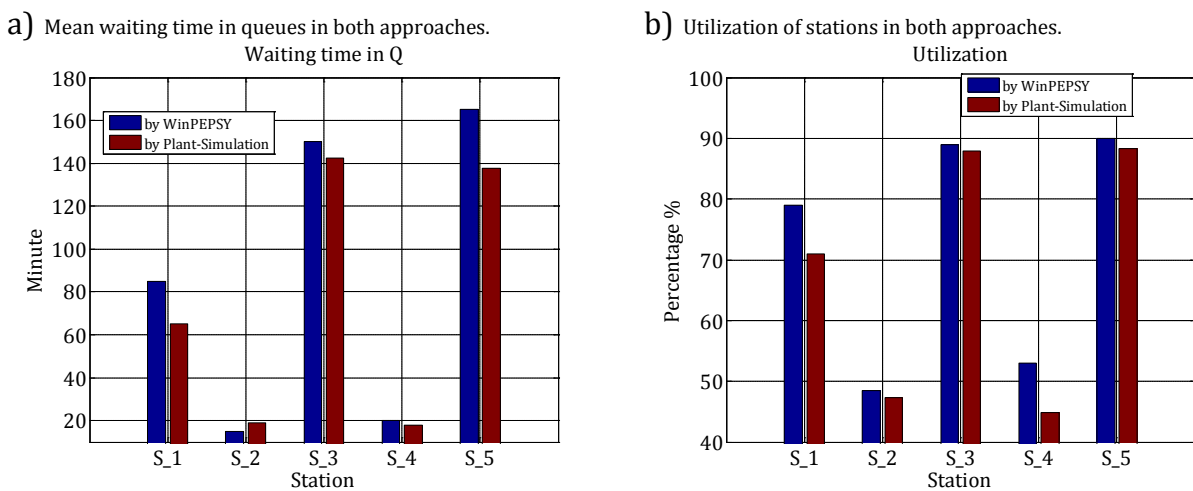
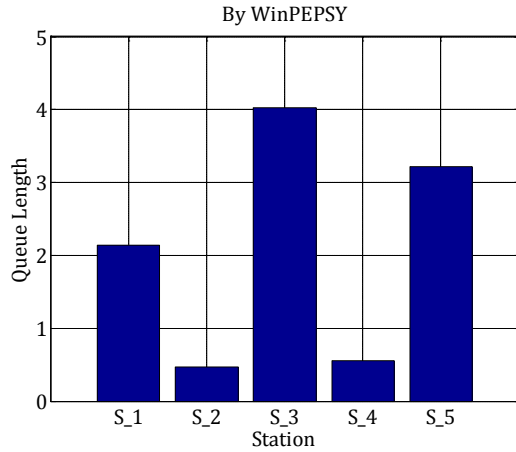


Figure 93: Waiting time and utilization with Plant simulation and WinPEPSY.

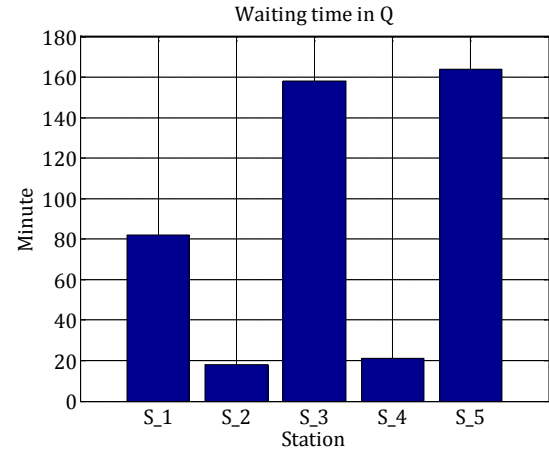
a) Length of queues by 3 products in class one and 7 in class

b) Mean waiting time in queues by 3 products in class one and 7

three.



in class three.



c) Utilization of stations by 3 products in class one and 7 products in class three.

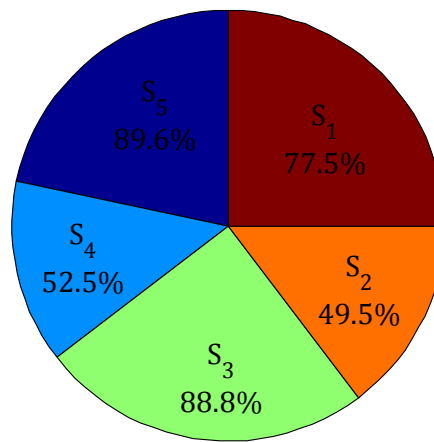


Figure 94: Sensitivity analysis for the number of jobs in queues, mean waiting time, and utilization with the use of closed queuing theory by WinPEPSY.

Figure 93a depicts the utilization of each station with the application of queuing theory and the use of discrete-event simulation model. Figure 93b compares both approaches in terms of the mean waiting times for all types in all queues. As it can be seen, these results have similarities in the magnitude, for both discrete-event and queuing network. The figures show the authenticity of the comparable queuing network model for this problem. Therefore, it is possible to perform a sensitivity analysis by the MVA algorithm. The chosen criterion for analysis is the number of jobs in classes. The results can be judged as follows. Figure 93c defines the utilization of the stations— using closed queuing network— when the number of products in class one changes from 5 to 3 and the products in class three change from 5 to 7. Figure 94a, Figure 94b, Figure 94c reflect the performance metrics under the scenario of 3 products in class one and 7 products in class three. However, these analysis metrics can be subjectively selected.

5.5.3 Extended RBF Network

However, an extension has been made to this current experiment in terms of RBF network. The extension is written in a paper by Mehraei *et al.* [391] accepted by 5th IEEE International Conference on Software, Knowledge, Information Management and Applications, SKIMA2011 in Italy. In that extended work, there exists a free number of RBFs in the hidden layer, each representing a pattern from inputs. Nevertheless, this time

three output functions are considered to reflect the three qualitative linguistic terms as (G), (N), and (B), see Figure 95. In contrast to the previous experiment, in this extended experiment just one network is considered for all stations, so that the global perception besides local decisions is given to Lpallets. Here, each RBF is supplementary to other two neighbor RBFs, in order to partially cover each of which.

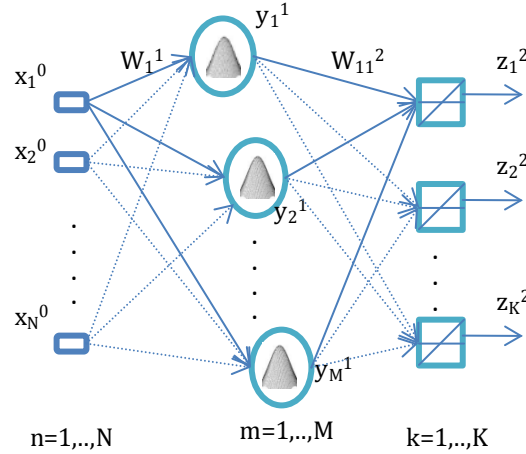


Figure 95: RBF network with unlimited RBFs in the hidden layer and three output functions to represent good, normal, and bad.

Accordingly, each Gaussian function covers (3σ) from its center, while the spread (σ) of each new embedded function is equal to the standard deviation of so far input data. Here, again the half-training of backpropagation is adopted to find the (inputs and outputs) weights of the network. However, the trainable factors are always exposed to learning new changes. In other words, throughout the running simulation each time an Lpallet meets a station the respective kern vector adapts itself to the new possible condition. In the initial training rounds, this adaption occurs by substituting the average of the last 3 recorded times of that respective station to the kern vector. However, each new recognized pattern builds a new RBF neuron. Indeed, when an input vector is not covered by the range of existing RBF (starting from first neurons to the last one) in the hidden layer, then this is assumed as a new pattern. So, in the hidden layer, a new RBF is configured with embedding the new input value as the center (kern vector) of the RBF. However, at the entrance of each station, there is a choice of getting in or over taking that. After training RBFNs each Lpallet as an individual module decides over its own sequence of operations. At the entrance of each station, every pallet is a decision maker for its respective operations' sequence. After several round trips of pallets instead of the actual waiting time as input the average of last three records for the corresponding station is taken as the real input to the RBFN. This results in a smoother perception to the dynamic waiting times.

5.5.4 Extended Scenario and Results

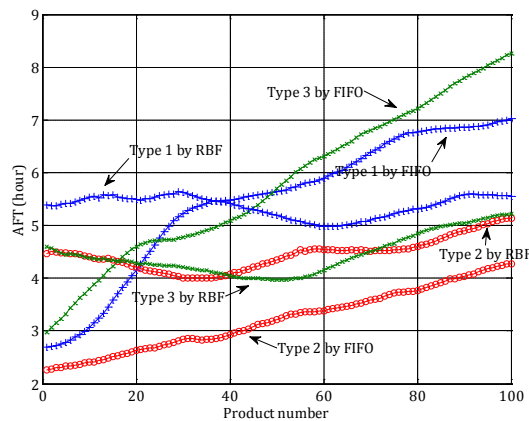
In this experiment again RBFN as an intelligent method is compared against the FIFO conventional dispatching rule. The FIFO dispatching rule is intentionally selected for the entire assembly line because of no available information about due dates and order batch-size in advance. In other words, each single supply of semi-finished products arrives

spontaneously with a stochastic manner, and they have to be promptly released to the system with real-time dispatching decision. Here, different alternative scenarios are examined. Variable (stochastic) and constant intervals in the replenishments— between supplies of semi-finished products to the entrance (un/load station) —as well as unbalanced processing times are the considered alternatives (scenarios). The scenarios are defined with the intention of depicting the performances of Lpallets under different circumstances. Furthermore, working time, waiting time, and blocked time of each station as well as average flow time (AFT) of finished products and makespan (completion time of last product) of all orders (150 each type) are the criteria to be compared. Here, the blocked time is the time that a product is asking for operation on a machine, but the machine is busy. In contrary, the waiting time is the time that machine is waiting for a product to be processed on. Table 21 defines the specification of the three alternative scenarios. Figure 96a and Figure 96b depict the stable performance of Lpallets with RBFN versus FIFO dispatching rules in the permutation flow shop. It can be seen that in both scenarios, the use of RBF leads to smoother AFT with a convergence tendency. Table 22 shows the numerical results in details for each of the scenarios.

Table 21: Examined scenarios with three alternatives.

| Scenario | Process time of each station | | | | | Supply inter-arrival time for each product type | | | Setup time | | | | |
|----------|--|---|---|---|---|---|---|---|----------------|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 1 | Neg. Exp with $\beta=10$ min, for all | | | | | Neg. Exp with $\beta=50$ min, for all | | | 5 min, for all | | | | |
| 2 | Neg. Exp with $\beta=10$ min, for all | | | | | Constant 50 min | | | 5 min, for all | | | | |
| 3 | $\beta_1=8, \beta_2=8, \beta_3=8, \beta_4=10, \beta_5=8$ | | | | | Constant 45 min | | | 5 min, for all | | | | |

a) Scenario 1: AFT for three product types by RBF vs. FIFO



b) Scenario 2: AFT for three product types by RBF vs. FIFO

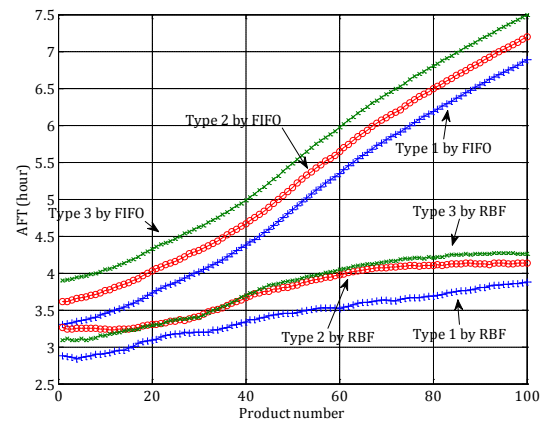


Figure 96: AFT with RBF vs. FIFO flow control in scenario 1 and 2.

Table 22: Performance of RBF against flow-shop with FIFO (Permutation flow shop) in stations and flow times.

| Performance of RBF against flow-shop with FIFO | | | | | |
|--|---------|---------|---------|---------|---------|
| Station | | | | | |
| | 1 | 2 | 3 | 4 | 5 |
| Scenario 1 | | | | | |
| RBFN | | | | | |
| Working | 60.97 % | 54.82 % | 58.41 % | 55.73 % | 53.45 % |
| Waiting | 19.36 % | 25.77 % | 21.67 % | 23.91 % | 26.7 % |

| | | | | | |
|--------------------|-----------------------|---------|---------|---------|---------|
| Blocked | 19.67 % | 19.42 % | 19.92 % | 20.36 % | 19.86 % |
| Av.Flow time (AFT) | 3.06 hour | | | | |
| Makespan | 5 day+12 hour+ 37 min | | | | |
| Flow shop- FIFO | | | | | |
| Working | 53.66 % | 52.83 % | 54.95 % | 54.49 % | 59.85 % |
| Waiting | 24.84 % | 25.67 % | 23.55 % | 24.01 % | 18.64 % |
| Blocked | 21.5 % | 21.5 % | 21.5 % | 21.5 % | 21.5 % |
| AFT | 3.04 hour | | | | |
| Makespan | 5 day+15 hour+ 39 min | | | | |
| Scenario 2 | | | | | |
| RBFN | | | | | |
| Working | 57.28 % | 57.66 % | 61.7 % | 57.5 % | 57.72 % |
| Waiting | 21.13 % | 22.63 % | 15.61 % | 21.17 % | 20.24 % |
| Blocked | 21.59 % | 19.71 % | 22.69 % | 21.33 % | 22.04 % |
| AFT | 3.18 hour | | | | |
| Makespan | 5 day+8 hour+ 33 min | | | | |
| Flow shop- FIFO | | | | | |
| Working | 55.54 % | 54.29 % | 57.54 % | 54.14 % | 50.5 % |
| Waiting | 16.99 % | 18.24 % | 14.99 % | 18.39 % | 22.03 % |
| Blocked | 27.47 % | 27.47 % | 27.47 % | 27.47 % | 27.47 % |
| AFT | 3.49 hour | | | | |
| Makespan | 5 day+16 hour+ 31 min | | | | |
| Scenario 3 | | | | | |
| RBFN | | | | | |
| Working | 51.42% | 50.73 % | 56.23 % | 63.23 % | 50.67 % |
| Waiting | 24.13 % | 26.25 % | 19.82 % | 11.11 % | 25.31 % |
| Blocked | 24.45 % | 23.03 % | 23.95 % | 25.66 % | 24.02 % |
| AFT | 2.85 hour | | | | |
| Makespan | 4 day+20 hour+53 min | | | | |
| Flow shop- FIFO | | | | | |
| Working | 51.62 % | 49.11 % | 50.97 % | 61.22 % | 48.75 % |
| Waiting | 17.33 % | 19.83 % | 17.97 % | 7.73 % | 20.2 % |
| Blocked | 31.06 % | 31.06 % | 31.06 % | 31.06 % | 31.06 % |
| AFT | 3 hour | | | | |
| Makespan | 5 day+44 min | | | | |

5.5.5 Conclusion of the Experiment

In this experiment, a new assembly scenario has been introduced that resembles a hybrid flow-open shop real-time scheduling problem. One conventional dispatching rule (FIFO) for complying with real-time allocation of materials in such assembly systems has been compared against three intelligent methods for real-time decision making and learning i.e., GA, fuzzy system, and ANN. In the initial experiments, the applied RBF networks have been assigned exclusively to each station. In other words, each station had its own parameters in the RBF network embedded in each Lpallet. So, there was no real global perception about the system just the changes in the condition of station in terms of processing and waiting times affect the changes in the RBF network. On the contrary, in the extended experiment on the same assembly scenario, the RBF network embedded in each Lpallet has been used universally for all stations. Therefore, the perception about each station has been dependent on the performance of the other stations in general. With this respect, the global perception about the entire assembly system is given to Lpallets, so that their decisions are

pertinent to others' performances. In doing so, the shortcoming about the lack of global awareness of autonomous objects in confronting dynamics can be, to some extent, solved. However, in spite of relatively long term training for MLP and the variable number of layers with direct effect on the output quality, MLP network seems irrelevant for Lpallets with the mission of real-time training as well as decision making under highly transient production circumstances.

Moreover, in the initial experiment GA and fuzzy controller have shown their competency in running Lpallets with real-time scheduling and control tasks. It is noticeable that each of the experimented intelligent techniques may be tuned in different ways with much better performances. This is one of the future works proposed by the current study. Additionally, it has been proved that analysis with queuing theory can be compared by the results out of Lpallets in discrete-event simulation. It has been shown that plausibility of decisions done by Lpallets in real-time are not worse than the conventional analysis results by closed queuing network with offline solutions. This fact illustrates the suitability of Lpallets in practice. Moreover, this assembly scenario has another variant, which is presented in the paper by Mehraei and Scholz-Reiter [392]. There the performance of GA and fuzzy system is compared with FIFO dispatching rule done by LISA conventional scheduling software.

6 Physical Implementation of Prototype

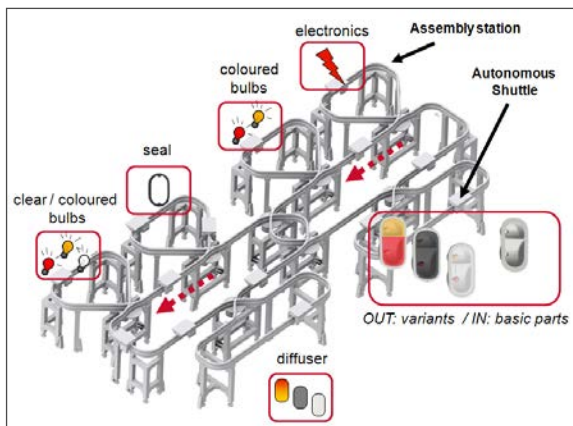
The state of the art in ICT has gradually facilitated the realization of autonomous agents in academic labs as well as some experimental implementations. One of the most abundantly used technologies to carry the mission of data storage (and further processing) is RFID, which is currently very much used in industrial applications, e.g., for tracing materials and identification. As a matter of fact, cheap price, relatively reasonable memory capacity, tags with flexibility forms, and adjustable applications, make the RFID technology quite suitable for intelligent products towards autonomy. This issue is recently addressed in autonomous products by CRC 637 research cluster at Bremen University, for more information see www.sfb637.uni-bremen.de.

However, RFID tags as pure data collection memories are clustered in the category of passive data processing nodes (even if in active or passive forms) with no self-computational competence. In other words, the computing operations have to be transferred to another computing object and they have no capability in this regard. This fact makes them impractical means of ICT; to be used by autonomous controlled logistics objects with the requirement of self-organized decision making. On the contrary, WSN are another means of ICT to be investigated by CRC 637 research cluster for autonomous controlled objects, see Figure 97. These WSN have some capabilities, which made them suitable to be employed by the project of intelligent containers in the same research cluster. Among these competencies of WSN, their abilities in collecting and processing data, interacting with their environments via sensors, communicating with each other, and monitoring other objects, which can be directly used in logistic operations, have underlined this state-of-the-art. For more information about the WSN (Telos), see [393].



Figure 97: Exemplary wireless sensor nodes.

For the purpose of developing prototypes of Lpallets, it was decided to employ wireless nodes with limited computations as well as communication abilities. In the final part of this study, this importance has been occurred by means of connecting WSN directly to the already developed simulation scenario. In the model of the assembly line developed in the Plant - Simulation package, the module of TCP/IP (communication protocol) socket has been employed to integrate the WSN as representatives of Lpallets to an assembly scenario. This has been done to experiment on the performance of the real WSN in rendering control decisions for assembly lines, see Figure 98.



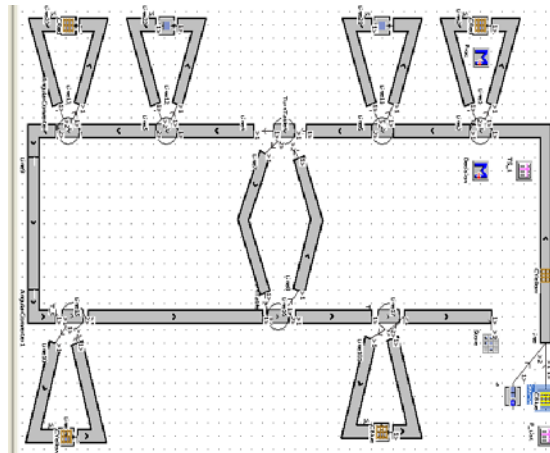
Assembly Scenario of CRC Demonstrator



Exemplary Prototype of Lpallets



Converting the
Scenario into
Simulation Model



Plant-Simulation

Figure 98: Integration of WSN representing Lpallets in the rare light assembly scenario of CRC 637 by means of simulation and TCP/IP protocol.

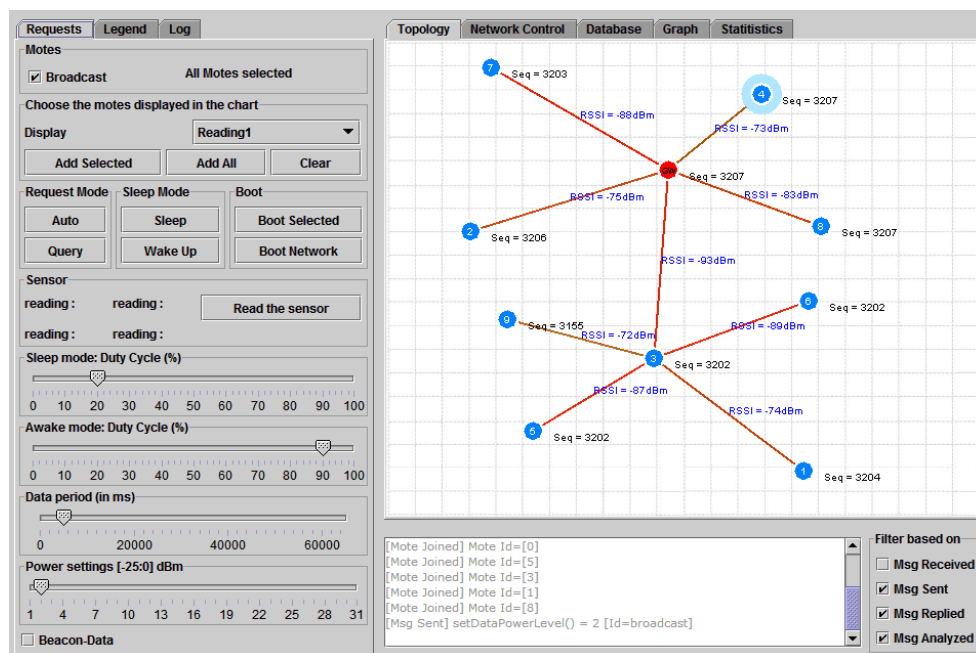


Figure 99: A Java-based control system for monitoring the performance of connecting WSN by means of TCP/IP [394].

Figure 99 displays the monitoring package for some connected WSN, each representing an Lpallet. This package is developed in a pertinent doctoral work to centrally observe the performance of distributed WSN in terms of power supply, strength of data transfer, proper communication, and so forth, within an open environment, for more information see [394].

The procedure of connecting WSN, or wireless node (WN) in general, to the simulation scenario and the use of them in representing Lpallets can be shortly described by the flow chart, shown in Figure 100.

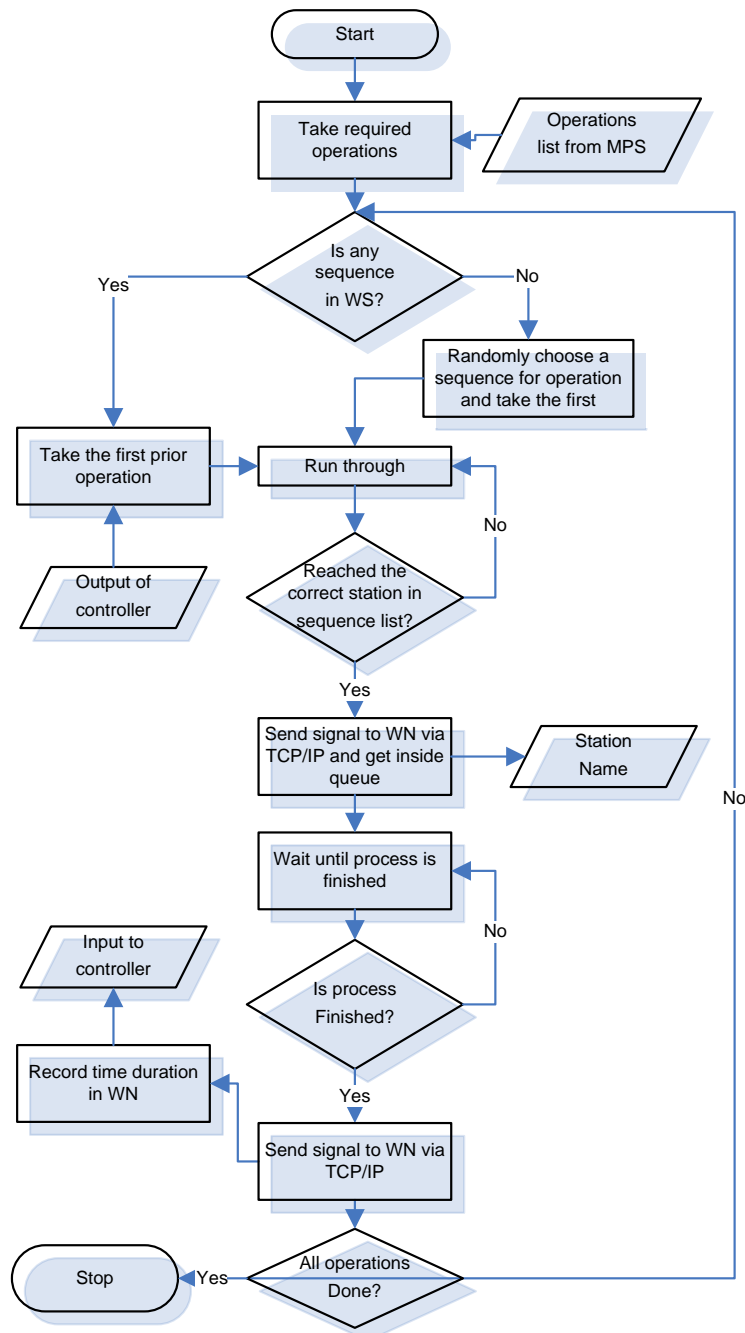


Figure 100: Flow chart of processes of connecting WSN as Lpallets to assembly scenario.

Concerning the limited memory and computational capacity, in this level of prototype development just a simple algorithm has to be applied. In fact, instead of the sophisticated algorithms explained in the chapter of experiment scenarios, here, the used algorithm is easily inspired by Little's law, which is deeply described in queuing theory. Each node, representing an Lpallet, collects information about waiting time at every station and builds a list of waiting times in each visiting event from every station. This leads to a matrix of waiting times collected in different events. In this regard, each Lpallet derives the length of queues for every station; according to the moving average value of experienced waiting times for each station and the current service rate of each station by (4.1.2).

$$\lambda_s = \rho_s \varepsilon_s \quad (4.1.1)$$

$$L_s = \lambda_s W_s \quad (4.1.2)$$

where ρ_s is the current record of utilization for station s , and ε_s is the service rate of station s , which is considered constant over the simulation horizon. Eventually, according to the real-time values about utilization of each station every WN approximates the queue length of the respective station. Upon that a priority list (sequencing) for operations can be configured. However, this sequence list is dynamic and after completion of each operation it is recalculated according to the current situation of the system (utilization and waiting times). Figure 101 defines the procedure of calculating and controlling the operations' sequence in WN.

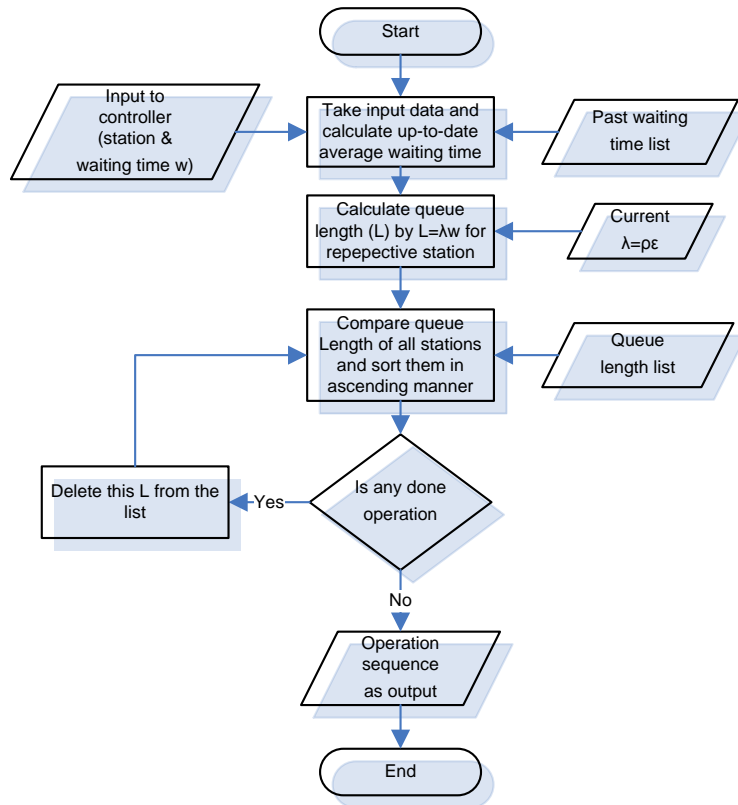


Figure 101: Flow chart of Little's law controller inside WN for choosing next operation in real-time.

In conclusion, Table 23 shows again the conditions of the three scenarios and Table 24 depicts some numerical data derived from this strategy (Little's Law) for the aforementioned hybrid flow-open shop problem, in the extended version of RBFN in the final experiment of the last section. The results are quite comparable with RBFN and even show a bit better performance. This can be explained by the simple procedure of this strategy. It can be judged that because of the simplicity of the scenario, the straightforward strategy requires no complex and long-term learning procedure, thereby, in turn presents better outputs.

Table 23: Examined scenarios with the three alternatives.

| Scenario | Process time of each station | | | | | Supply inter-arrival time for each product type | | | Setup time | | | | |
|----------|--|---|---|---|---|---|---|---|----------------|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 1 | Neg. Exp with $\beta=10$ min, for all | | | | | Neg. Exp with $\beta=50$ min, for all | | | 5 min, for all | | | | |
| 2 | Neg. Exp with $\beta=10$ min, for all | | | | | Constant 50 min | | | 5 min, for all | | | | |
| 3 | $\beta_1=8, \beta_2=8, \beta_3=8, \beta_4=10, \beta_5=8$ | | | | | Constant 45 min | | | 5 min, for all | | | | |

Table 24: Performance of Lpallets with the use of Little's law.

| Performance of Lpallets with the use of Little's law | | | | | |
|--|----------------------|---------|---------|---------|---------|
| Station | | | | | |
| | 1 | 2 | 3 | 4 | 5 |
| Scenario 1 | | | | | |
| Little's Law | | | | | |
| Working | 52.36 % | 59.23 % | 58.08 % | 56.15 % | 55.33 % |
| Waiting | 25.17 % | 19.48 % | 20.10 % | 21.25 % | 22.46 % |
| Blocked | 22.47 % | 21.30 % | 21.82 % | 22.60 % | 22.21 % |
| Av.Flow Time (AFT) | 2.91 hour | | | | |
| Makespan | 5 day+7 hour+ 33 min | | | | |
| Scenario 2 | | | | | |
| Little's Law | | | | | |
| Working | 54.84 % | 61.09 % | 54.61 % | 57.86 % | 57.58 % |
| Waiting | 24.22 % | 17.71 % | 25.55 % | 21.00 % | 20.96 % |
| Blocked | 20.94 % | 21.20 % | 19.83 % | 21.13 % | 21.46 % |
| AFT | 2.94 hour | | | | |
| Makespan | 5 day+8 hour+ 08 min | | | | |
| Scenario 3 | | | | | |
| Little's Law | | | | | |
| Working | 50.45 % | 49.16 % | 53.25 % | 64.95 % | 49.52 % |
| Waiting | 25.29 % | 28.15 % | 23.63 % | 11.15 % | 26.71 % |
| Blocked | 24.27 % | 22.69 % | 23.12 % | 23.91 % | 23.76 % |
| AFT | 2.87 hour | | | | |
| Makespan | 4 day+20 hour+25 min | | | | |

7

Conclusion and Outlook

7.1 Conclusion

In conclusion, it can be claimed that the current study has broadly complied with the notion of feasibility study in interpreting autonomous logistics in practice. In fact, the present and prospective situations of dynamics in logistics' practices have initiated the current work. Accordingly, the main target of the work has been located on the issue of handling the dynamics in logistics. Since in literature one of the most advanced strategies to deal with dynamics and complexities is *autonomy*, the major effort has thoroughly been put on this topic. In the beginning, the fairly detailed exploration of the state of the art in current organizational processes— in terms of logistics and SCM— has facilitated the notion of feasibility study for the autonomy paradigm. Basically, here, the autonomy paradigm in logistics has been classified into two major features as *autonomous logistic processes* and *autonomous logistic objects*. Indeed, by means of this classification, both macro features of autonomy in logistics as well as micro perspectives of that in practice are reasonably covered. With this respect, the current study has been divided into conceptual and empirical parts. Hence, the initial chapters have rather addressed the conceptual issues, regarding dynamics and autonomy, whereas the latter chapters have more emphasized on empirical approaches for the feasibility of the conceptual parts.

Moreover, it has been shown that the autonomy can be competently used in operational levels, since it focuses on local and decentralized decision making and executions, as well as relying on local information. However, in the current tactical and strategic practices in logistics, the autonomy paradigm seems impractical, since coordination in aggregated levels plays a crucial role in effective and efficient achievements. In this respect, the superior contributions of the autonomy to the concurrent production strategies and SCM (e.g., mass-customization, MTO, pull control, detailed scheduling) have been underscored. Here, it has been discussed that some specific material flow control systems, like pull control, are in congruence with the decentralization, the individualization, and the distributed features of the autonomy. Thus, the roles of material pull control and other competent strategies have been fairly discussed in the chapters. Correspondingly, the aspects of planning and scheduling in detailed and preferably in operational level have been taken into account. This approach has led the study to more elaborations in terms of scheduling and mathematical programming. In doing so, the focal area of the autonomy's practices in this study has been concretized and justified. To this level, the feasibility study has spanned most of the relevant aspects of logistics to autonomy merit. For instance, it was mentioned that by realizing autonomy in logistics a great assistance happens to the mass-customization goal in industries with individualized orders, or scheduling in real-time can be facilitated. It is noticeable that until this era, the work has been more focusing on the first aspect of autonomy (autonomous logistic processes).

Afterwards, the study has started to proceed with another importance of autonomy, regarding the issue of autonomous logistic objects. Basically, it has been observed that the suggestions and claims about the contribution of autonomous processes to logistics have to be accompanied with some tangible outcomes. Therefore, the concept of Lpallets has been

respectively emerged to the subsequence of this work. Then, in order to develop the novel idea about feasible objects in logistics— with the competency of undertaking the autonomy merit— investigations for some intelligent methodologies have become important. By concentrating on the notion of *machine learning* and *AI* some prominent techniques of them has been emphasized. Later, despite the broad investigation's space in the highlighted methodologies, it has been tried to explore moderately the famous features in these aforementioned fields. Therefore, *ANN*, *GA*, and *Fuzzy system* rather than other techniques have been in details explored. Indeed, each of these techniques can proceed with some specific aspects of learning and intelligent decision making in manufacturing and logistics operations. For instance, *GA* has shown its competency in those scheduling environments with a relatively lower pace in volatility, regarding its global search specification. On the contrary, *ANN* and fuzzy controller are able to make a fairly quick adaptation to new circumstances, nonetheless, with less attention to the global performance of the respective and other intelligent objects. However, in the current work each of these techniques has been covered in small variants, since each of them can be an individual research topic in the field of learning and intelligent logistic objects with further work potentials.

Moreover, with respect to the fact that operational processes have to be in compliance with the tactical planning outputs, mathematical programming has been concisely introduced. Indeed, the concise contribution of the current work to tactical planning and scheduling processes has directly been placed on the issue of fuzzy mathematical programming. This underscored harmony has been reflected by the moderated freedoms in decision parameters of fuzzy mathematical programming, which later can be used by autonomous objects to make real-time decisions in logistics. However, this exploration is not extended in the current work and is open for further elaborations. Afterwards, with the purpose of analyzing the performance of *Lpallets* in shop-floors the queuing theory has been briefly studied. There it has been seen that the performance of *Lpallets* within production lines and *SC* can be assimilated to the notion of queuing networks. With this purpose, the general behaviors of *Lpallets* in such production networks can be reasonably justified by closed networks. Obviously, investigation in *Lpallets'* routing decisions, by means of closed queuing networks, has given rise to the fact that *Lpallets* make relatively logical and intelligent decisions.

Furthermore, to prove the claims in the feasibility study overall the work, several simulations scenarios have been developed and experimented. Indeed, in this level of research the only available and the most reliable tool for justifying the recommendations resulted from the study has been the simulation. In this regard, the primary experiment scenarios attempted to resemble macro scale logistics' operations and sought to reveal the notion of autonomy in conventional logistics. In further experiments with more emphasis on *Lpallets*, the scenarios focused on shop-floor performances and directly modeled some relevant scenarios to other autonomy studies. The 3×3 flexible shop-floor as well as the assembly shop-floor with five (5) stations both have been inspired by two sections of research cluster CRC 637 <http://www.sfb637.uni-bremen.de/>. Specially, the assembly

scenario has directly modeled the prototype of a car's lights assembly line, available at the lab of BIBA Institute affiliated to Bremen University. In the later experiments, the superior performance of Lpallets— confronting with transient and fluctuating conditions (dynamics) — in particular for scheduling and control is illustrated.

All in all, it is fair to claim that this feasibility study with the following framework Figure 102 is a novel research in developing a practice oriented exploration for autonomy in logistics. The novel advantage of the introduced Lpallets is their full decentralized practices in simulation and satisfactory results in their performances. Moreover, in addition to the already developed autonomous control methods, the fuzzy controller, ANN, and GA methods, introduced in this study, positively contribute to the attempts towards the realization of practical autonomous objects in logistics. This commitment gives rise to more competitive and modern industries with the capability of agility. Pallets and similar logistic objects are quite likely to assist this ambition of factories of the future. Thus, it is quite fair to claim that Lpallets are novel and, simultaneously, one of the most feasible logistic objects in practice, which can be autonomous. This statement has been partially proven by simulation and, in further works, it has to be experimented and justified in practice, by closer cooperation with industry.

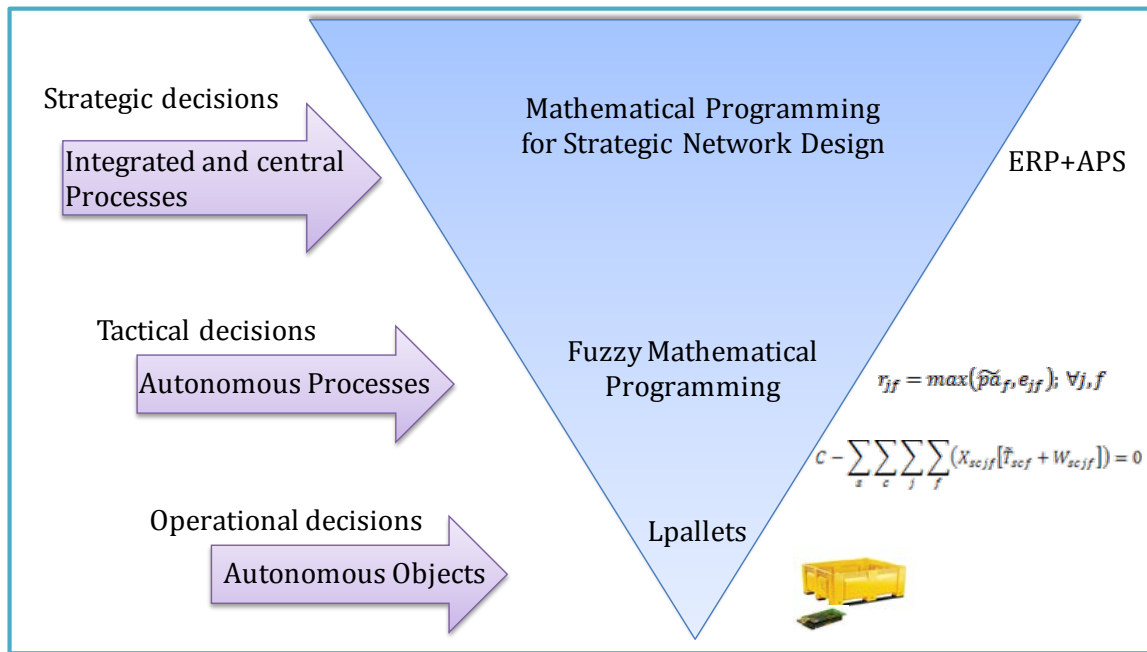


Figure 102: The general proposed framework in the study.

7.2 Outlook

On the basis of the optimistic results concluded by this study, several opportunities have evolved for further works. Indeed, the most important concern about the general concept of autonomy in logistics is to bring it into reality. Thus, focusing on the feasibility issue, for different logistic systems as well as logistic objects, plays a crucial role in developing, improving, and implementing autonomy in logistics. In this manner, by taking into account

the two correlated features in the autonomy (i.e., autonomous processes and autonomous object), some recommendations for further works are following:

- Enhancing the proposed framework upon more precise positioning of autonomous processes between conventional processes in manufacturing industries.
- Defining the interfaces between the suggested autonomous processes, in operational level, as well as tactical and strategic planning processes,
 - Implementing the required (recommended) freedoms in the planning and optimizing packages like APS and embedding the autonomous operational decisions (made by autonomous objects), by means of calibrations,
 - Combining the fuzzy and stochastic mathematical programming—using offline optimization solutions— with decentralized autonomous decisions made in real-time at operational levels, by deep explorations in both real-time decisions and offline optimizations,
 - Extending the role of operational autonomous decisions in relaxing the complex tactical and operational offline planning and scheduling,
 - Experimenting on the contribution of autonomous processes in improving the ATP/CTP capability to increase responsiveness in advanced companies.
- Developing the introduced concept about Lpallets with regard to the further technical requirements as well as the algorithms for decision making,
 - The small experimented prototype of Lpallets has been done by means of a specific WSN, additional state of the art in such technologies must be deeply explored and classified according to the working environment and required performances,
 - In this work, some general intelligent techniques like ANN, GA, and fuzzy system have been employed to render complex decisions. Nevertheless, each of the techniques has several variants, which can be investigated regarding different circumstances in terms of inputs and outputs of controllers,
 - Application of the intelligent techniques in managing complexities in higher scales like SC and SN, by make use of ANN, GA, and fuzzy system, for making complex decisions in material flows, even in an offline manner.
- Investigating the extended contribution of ANN to Lpallets in more sophisticated decision atmosphere,
 - Expanding the training of the explored RBF network from half training to full training phase,
 - Exploring the effect of other variants in ANN above RBF, like recurrent networks, towards superior learning by more intensified feedback (closed-) loops for autonomous Lpallets,
 - Extending the learning algorithms from backpropagation (by gradient descent) to other competent algorithms, which partly were introduced in the ANN section,
 - Considering involvement of GA and other evolutionary algorithms in training ANN for larger solution space,

- Applying ANN for function approximation in proactively predicting the behaviors of stations as well as entire logistic systems.
- Expanding the study about intelligent methods for autonomous objects with more precise results from GA, SA, and fuzzy system,
 - Considering memetic algorithms in exact adaptation of GA in facing dynamics within less time,
 - Elaborating the performance of GA by moving towards genetic programming for alternative situations and making use of different programs at the same time for more intelligent performances,
 - Adjusting SA and tabu search techniques in order to be used as real-time intelligent methods for Lpallets and comparing them against other methods, e.g., GA.
- Configuring some hybrid aspects of the listed intelligent methods in order to improve the performance of decision making, e.g., neuro-fuzzy and genetic neuro-fuzzy, see Figure 103.
- Developing the extended and more general form of protocols as well as algorithms for Lpallets to cover further tasks in logistics, in addition to more criteria (KPI) in learning the behaviors,
 - Mounting protocols in connecting wireless autonomous objects (e.g., WSN), with the purpose of negotiating between objects and intelligent resources in logistics (e.g., machines),
 - Extending some algorithms with the capability of evaluating and analyzing complex criteria in logistics (e.g., rate of supply and demand, real-time changes in orders) to make more exact operational decisions.
- Investigating the exact contribution of Lpallets (or alike logistic objects) in practical operations, as the ultimate target and major outlook of this study.

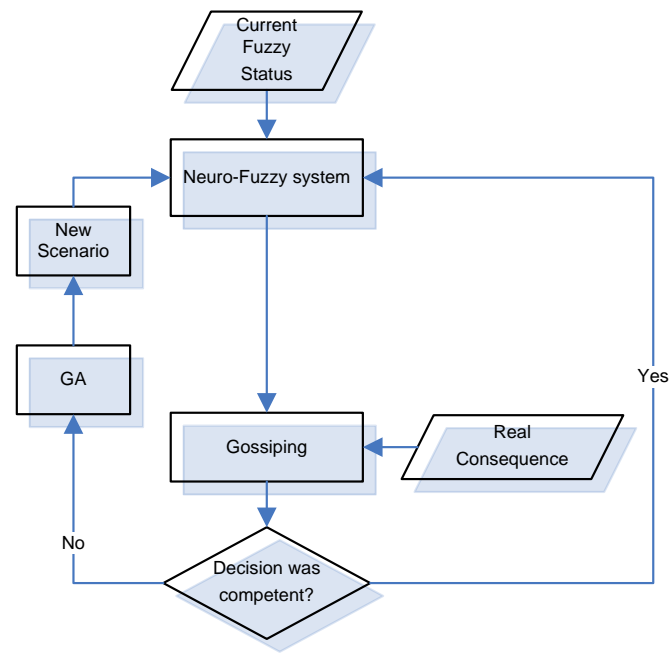


Figure 103: An exemplary cooperation between ANN, Fuzzy system, GA, and Gossiping (Epidemic) method for up-to-dating reactions to changes in an autonomous environment.

On the top of the mentioned outlooks, it has to be emphasized on the issue of synchronization of autonomous decentralized decisions in real-time with fuzzy and stochastic mathematical programming in tactical level. Doubtless fuzzy and stochastic parameters are inherent features in practical operations. Thus, they must be taken into account as a great further working potential of the current study. This can be realized by means of developing some competent mathematical programming (e.g., fuzzy optimization). Since mathematical programming is the basis of any planning optimization packages (e.g., APS), adjustment of autonomous operations to the mathematical models is essential. However, a deep exploration in the area is required to investigate the solutions of fuzzy mathematical programming, in addition to more precise performances of autonomous objects in association with fuzzy mathematical programming.

References

- [1] Obizhaeva, A. and Wang, J., *Optimal Trading Strategy and Supply/Demand Dynamics*. 2005, National Bureau of Economic Research Cambridge, Mass., USA.
- [2] Stuer, G., Vanmechelen, K., and Broeckhove, J., *A Commodity Market Algorithm for Pricing Substitutable Grid Resources*. *Future Generation Computer Systems*, 2007. 23(5): p. 688-701. ISBN: 0167-739X.
- [3] Li, S., Murat, A., and Huang, W., *Selection of Contract Suppliers under Price and Demand Uncertainty in a Dynamic Market*. *European Journal of Operational Research*, 2009. 198(3): p. 830-847. ISBN: 0377-2217.
- [4] Liao, K., Marsillac, E., Johnson, E., and Liao, Y., *Global Supply Chain Adaptations to Improve Financial Performance: Supply Base Establishment and Logistics Integration*. *Journal of Manufacturing Technology Management*, 2010. 22(2): p. 204-222. ISBN: 1741-038X.
- [5] Wagner, C. and Nyhuis, P., *A Systematic Approach to Analysis and Design of Global Production Networks*. *Production Engineering*, 2009. 3(3): p. 295-303. ISBN: 0944-6524.
- [6] Beamon, B. M., *Sustainability and the Future of Supply Chain Management*. *Operations and Supply Chain Management*, 2008. 1(1): p. 4-18.
- [7] Christopher, M., *Logistics and Supply Chain Management: Creating Value-Added Networks*. 2005: Pearson education. ISBN: 0273681761.
- [8] Harland, C. M., *Supply Chain Management: Relationships, Chains and Networks*. *British Journal of management*, 1996. 7: p. S63-S80. ISBN: 1467-8551.
- [9] Wycisk, C., Mckelvey, B., and Hülsmann, M., *"Smart Parts" Supply Networks as Complex Adaptive Systems: Analysis and Implications*. *International Journal of Physical Distribution & Logistics Management*, 2008. 38(2): p. 108-125. ISBN: 0960-0035.
- [10] Li, G., Yang, H., Sun, L., Ji, P., and Feng, L., *The Evolutionary Complexity of Complex Adaptive Supply Networks: A Simulation and Case Study*. *International Journal of Production Economics*, 2009. 124(2): p. 310-330. ISBN: 0925-5273.
- [11] Croom, S., Romano, P., and Giannakis, M., *Supply Chain Management: An Analytical Framework for Critical Literature Review*. *European Journal of Purchasing & Supply Management*, 2000. 6(1): p. 67-83. ISBN: 0969-7012.
- [12] Hwarng, H. B. and Xie, N., *Understanding Supply Chain Dynamics: A Chaos Perspective*. *European Journal of Operational Research*, 2008. 184(3): p. 1163-1178. ISBN: 0377-2217.
- [13] Windt, K. and Hülsmann, M., *Changing Paradigms in Logistics–Understanding the Shift from Conventional Control to Autonomous Cooperation and Control*. In *Understanding Autonomous Cooperation & Control - the Impact of Autonomy on Management, Information, Communication, and Material Flow*, Hülsmann, M. and Windt, K., Editors. 2007, Springer: Berlin. p. 1-16. ISBN: 978-3-540-47449-4.
- [14] Schuh, G. and Gottschalk, S., *Production Engineering for Self-Organizing Complex Systems*. *Production Engineering*, 2008. 2(4): p. 431-435. ISBN: 0944-6524.
- [15] Lollini, P., Bondavalli, A., and Di Giandomenico, F., *A Decomposition-Based Modeling Framework for Complex Systems*. *Reliability, IEEE Transactions on*, 2009. 58(1): p. 20-33. ISBN: 0018-9529.
- [16] Dominici, G., Argoneto, P., Renna, P., and Cuccia, L., *The Holonic Production System: A Multi Agent Simulation Approach*. *iBusiness*, 2010. 2(3): p. 201-209. DOI: 10.4236/ib.2010.23025.
- [17] Keshavarz, N., Nutbeam, D., Rowling, L., and Khavarpour, F., *Schools as Social Complex Adaptive Systems: A New Way to Understand the Challenges of Introducing the Health Promoting Schools Concept*. *Social Science & Medicine*, 2010. 70(10): p. 1467-1474. ISBN: 0277-9536.
- [18] Nylund, H. and Andersson, P. H., *Framework for Extended Digital Manufacturing Systems*. *International Journal of Computer Integrated Manufacturing*, 2011. 24(5): p. 446-456. DOI: 10.1080/0951192X.2010.542179. ISBN: 0951-192X.
- [19] Aslam, T. and Ng, A., *Agent-Based Simulation and Simulation-Based Optimisation for Supply Chain Management*. In *Enterprise Networks and Logistics for Agile Manufacturing*, L., W.

- and S.C.L., K., Editors. 2010, Springer: London. p. 227-247. DOI: 10.1007/978-1-84996244-5. ISBN: 978-1-84996243-8.
- [20] Scholz-Reiter, B., Freitag, M., De Beer, C., and Jagalski, T., *Modelling Dynamics of Autonomous Logistic Processes: Discrete-Event Versus Continuous Approaches*. Cirp Annals-Manufacturing Technology, 2005. 54(1): p. 413-416. DOI: 10.1016/S0007-8506(07)60134-6.
 - [21] Pathak, S. D., Day, J. M., Nair, A., Sawaya, W. J., and Kristal, M. M., *Complexity and Adaptivity in Supply Networks: Building Supply Network Theory Using a Complex Adaptive Systems Perspective**. Decision Sciences, 2007. 38(4): p. 547-580. ISBN: 1540-5915.
 - [22] Meepetchdee, Y. and Shah, N., *Logistical Network Design with Robustness and Complexity Considerations*. International Journal of Physical Distribution & Logistics Management, 2007. 37(3): p. 201-222. ISBN: 0960-0035.
 - [23] Buckley, C. L., Bullock, S., and Barnett, L., *Spatially Embedded Dynamics and Complexity*. Complexity, 2010. 16(2): p. 29-34. ISBN: 1099-0526.
 - [24] Sarimveis, H., Patrinos, P., Tarantilis, C. D., and Kiranoudis, C. T., *Dynamic Modeling and Control of Supply Chain Systems: A Review*. Computers & Operations Research, 2008. 35(11): p. 3530-3561. ISBN: 0305-0548.
 - [25] Vlachos, D., Georgiadis, P., and Iakovou, E., *A System Dynamics Model for Dynamic Capacity Planning of Remanufacturing in Closed-Loop Supply Chains*. Computers & Operations Research, 2007. 34(2): p. 367-394. ISBN: 0305-0548.
 - [26] Kumar, S. and Yamaoka, T., *System Dynamics Study of the Japanese Automotive Industry Closed Loop Supply Chain*. Journal of Manufacturing Technology Management, 2007. 18(2): p. 115-138. ISBN: 1741-038X.
 - [27] Stermann, J. D., *Forthcoming in the Bullwhip Effect in Supply Chains*. O. Carranza and F. Villegas, (Eds.) Palgrave Mcmillan. *Operational and Behavioral Causes of Supply Chain Instability**. 2008.
 - [28] Váncza, J., Egri, P., and Monostori, L., *A Coordination Mechanism for Rolling Horizon Planning in Supply Networks*. Cirp Annals-Manufacturing Technology, 2008. 57(1): p. 455-458. ISBN: 0007-8506.
 - [29] Torabi, S. and Hassini, E., *An Interactive Possibilistic Programming Approach for Multiple Objective Supply Chain Master Planning*. Fuzzy Sets and Systems, 2008. 159(2): p. 193-214. ISBN: 0165-0114.
 - [30] Kanda, A. and Deshmukh, S., *Supply Chain Coordination: Perspectives, Empirical Studies and Research Directions*. International Journal of Production Economics, 2008. 115(2): p. 316-335. ISBN: 0925-5273.
 - [31] Jiao, J., You, X., and Kumar, A., *An Agent-Based Framework for Collaborative Negotiation in the Global Manufacturing Supply Chain Network*. Robotics and Computer Integrated Manufacturing, 2006. 22(3): p. 239-255. ISBN: 0736-5845.
 - [32] Lou, P., Zhou, Z., Chen, Y. P., and Ai, W., *Study on Multi-Agent-Based Agile Supply Chain Management*. The International Journal of Advanced Manufacturing Technology, 2004. 23(3): p. 197-203. ISBN: 0268-3768.
 - [33] Duffie, N., Roy, D., and Shi, L., *Dynamic Modeling of Production Networks of Autonomous Work Systems with Local Capacity Control*. Cirp Annals-Manufacturing Technology, 2008. 57(1): p. 463-466. ISBN: 0007-8506.
 - [34] Duffie, N. and Shi, L., *Maintaining Constant Wip-Regulation Dynamics in Production Networks with Autonomous Work Systems*. Cirp Annals-Manufacturing Technology, 2009. 58(1): p. 399-402. ISBN: 0007-8506.
 - [35] Scholz-Reiter, B., Görges, M., and Philipp, T., *Autonomously Controlled Production Systems--Influence of Autonomous Control Level on Logistic Performance*. Cirp Annals-Manufacturing Technology, 2009. 58(1): p. 395-398. ISBN: 0007-8506.
 - [36] Duffie, N. A., *Synthesis of Heterarchical Manufacturing Systems*. Computers in industry, 1990. 14(1-3): p. 167-174. ISBN: 0166-3615.
 - [37] Windt, K., Böse, F., and Philipp, T., *Autonomy in Production Logistics: Identification, Characterisation and Application*. Robotics and Computer-Integrated Manufacturing, 2008. 24(4): p. 572-578. ISBN: 0736-5845.

- [38] Bongaerts, L., Monostori, L., Mcfarlane, D., and Kádár, B., *Hierarchy in Distributed Shop Floor Control*. Computers in industry, 2000. 43(2): p. 123-137. ISBN: 0166-3615.
- [39] Phukan, A., Kalava, M., and Prabhu, V., *Complexity Metrics for Manufacturing Control Architectures Based on Software and Information Flow*. Computers & industrial engineering, 2005. 49(1): p. 1-20. ISBN: 0360-8352.
- [40] Prabhu, V. V., *Performance of Real-Time Distributed Arrival Time Control in Heterarchical Manufacturing Systems*. IIE Transactions, 2000. 32(4): p. 323-331. ISBN: 0740-817X.
- [41] Guttmann, C., *Towards a Taxonomy of Decision Making Problems in Multi-Agent Systems*. Multiagent System Technologies, 2009: p. 195-201.
- [42] Ivanov, D., Sokolov, B., and Kaeschel, J., *A Multi-Structural Framework for Adaptive Supply Chain Planning and Operations Control with Structure Dynamics Considerations*. European Journal of Operational Research, 2009. 200(2): p. 409-420. ISBN: 0377-2217.
- [43] Symeonidis, A. L., Kehagias, D. D., and Mitkas, P. A., *Intelligent Policy Recommendations on Enterprise Resource Planning by the Use of Agent Technology and Data Mining Techniques*. Expert Systems with Applications, 2003. 25(4): p. 589-602. ISBN: 0957-4174.
- [44] March, J. G., *Rationality, Foolishness, and Adaptive Intelligence*. Strategic Management Journal, 2006. 27(3): p. 201-214. ISBN: 1097-0266.
- [45] Macal, C. M. and North, M. J., *Tutorial on Agent-Based Modeling and Simulation*. Journal of Simulation, 2009. 4: p. 151-162. DOI: 10.1057/jos.2010.3.
- [46] Symeonidis, A. L., Kehagias, D., Koumpis, A., and Vontas, A., *Open Source Supply Chains*. International Journal of Agile Manufacturing (Invited Paper), 2005.
- [47] Labarthe, O., Espinasse, B., Ferrarini, A., and Montreuil, B., *Toward a Methodological Framework for Agent-Based Modelling and Simulation of Supply Chains in a Mass Customization Context*. Simulation Modelling Practice and Theory, 2007. 15(2): p. 113-136. ISBN: 1569-190X.
- [48] Scholz-Reiter, B. and Mehraei, A., *Superior Performance of Leagile Supply Networks by Application of Autonomous Control*. Advances in Production Management Systems. New Challenges, New Approaches, 2010: p. 333-341.
- [49] Böse, F., Piotrowski, J., and Scholz-Reiter, B., *Autonomously Controlled Storage Management in Vehicle Logistics—Applications of Rfid and Mobile Computing Systems*. International Journal of RF Technologies: Research and Applications, 2009. 1(1): p. 57-76. ISBN: 1754-5730.
- [50] Hülsmann, M., Windt, K., Wycisk, C., Philipp, T., Grapp, J., and Böse, F. *Identification, Evaluation and Measuring of Autonomous Cooperation in Supply Networks and Other Logistic Systems*. In the 4th International Logistics and Supply Chain Congress. Izmir, Turkey. 2006: Citeseer.
- [51] Dolgui, A. and Proth, J. M., *Supply Chain Engineering: Useful Methods and Techniques*. 2010, London Heidelberg New York: Springer-Verlag. DOI: 10.1007/978-1-84996-017-5. ISBN: 978-1-84996-016-8.
- [52] Scholz-Reiter, B. and Freitag, M., *Autonomous Processes in Assembly Systems*. Cirp Annals-Manufacturing Technology, 2007. 56(2): p. 712-729.
- [53] Sun, H. and Venuvinod, P. K., *The Human Side of Holonic Manufacturing Systems*. Technovation, 2001. 21(6): p. 353-360. ISBN: 0166-4972.
- [54] Scholz-Reiter, B., Mehraei, A., and Görges, M., *Handling Dynamics in Logistics-Adoption of Dynamic Behaviour and Reduction of Dynamic Effects*. Asian International Journal of Science and Technology in Production and Manufacturing Engineering (AIJSTPME), 2009. 2(3): p. 99-110.
- [55] Sarkis, J., *An Empirical Analysis of Productivity and Complexity for Flexible Manufacturing Systems*. International Journal of Production Economics, 1997. 48(1): p. 39-48. ISBN: 0925-5273.
- [56] Hsieh, F. S., *Design of Reconfiguration Mechanism for Holonic Manufacturing Systems Based on Formal Models*. Engineering Applications of Artificial Intelligence, 2010. ISBN: 0952-1976.
- [57] Gao, G. H., Guo, M., and Li, N., *The Research of Distributed Manufacturing System Based on Agent*. Advanced Materials Research, 2011. 143: p. 448-451. ISBN: 1662-8985.

- [58] Liang, W. Y. and Huang, C. C., *The Agent-Based Collaboration Information System of Product Development*. International Journal of Information Management, 2002. 22(3): p. 211-224. ISBN: 0268-4012.
- [59] Trappey, A. J. C. and Hsiao, D. W., *Applying Collaborative Design and Modularized Assembly for Automotive Odm Supply Chain Integration*. Computers in industry, 2008. 59(2-3): p. 277-287. ISBN: 0166-3615.
- [60] Lu, L. and Wang, G., *A Study on Multi-Agent Supply Chain Framework Based on Network Economy*. Computers & industrial engineering, 2008. 54(2): p. 288-300. ISBN: 0360-8352.
- [61] Sterman, J. D., *Business Dynamics: Systems Thinking and Modeling for a Complex World*. 2000: McGraw Hill Higher Education. ISBN: 0071179895.
- [62] Sanchez, L. M. and Nagi, R., *A Review of Agile Manufacturing Systems*. International Journal of Production Research, 2001. 39(16): p. 3561-3600. ISBN: 0020-7543.
- [63] Wiendahl, H. P., Elmaraghy, H., Nyhuis, P., Zäh, M., Wiendahl, H. H., Duffie, N., and Brieke, M., *Changeable Manufacturing-Classification, Design and Operation*. Cirp Annals-Manufacturing Technology, 2007. 56(2): p. 783-809. ISBN: 0007-8506.
- [64] Barták, R., Salido, M. A., and Rossi, F., *Constraint Satisfaction Techniques in Planning and Scheduling*. Journal of Intelligent Manufacturing, 2010. 21(1): p. 5-15. ISBN: 0956-5515.
- [65] Klaus, H., Rosemann, M., and Gable, G. G., *What Is Erp?* Information Systems Frontiers, 2000. 2(2): p. 141-162. DOI: 10.1023/A:1026543906354. ISBN: 1387-3326.
- [66] Robert Jacobs, F. and Ted'weston, F., *Enterprise Resource Planning (Erp)--a Brief History*. Journal of Operations Management, 2007. 25(2): p. 357-363. ISBN: 0272-6963.
- [67] Stadtler, H. and C., K., *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*. 4th ed. ed. 2008, Berlin Heidelberg: Springer-Verlag. ISBN: 978-3-540-74511-2.
- [68] Chen, I. J., *Planning for Erp Systems: Analysis and Future Trend*. Business Process Management Journal, 2001. 7(5): p. 374-386. ISBN: 1463-7154.
- [69] Günther, H. O., *Supply Chain Planning and Advanced Planning Systems Part Ii, Lecture Notes*. 2006, Technical University of Berlin: Berlin.
- [70] Karaarslan, N. and Gundogar, E., *An Application for Modular Capability-Based Erp Software Selection Using Ahp Method*. The International Journal of Advanced Manufacturing Technology, 2009. 42(9): p. 1025-1033. ISBN: 0268-3768.
- [71] Botta-Genoulaz, V., Millet, P. A., and Grabot, B., *A Survey on the Recent Research Literature on Erp Systems*. Computers in industry, 2005. 56(6): p. 510-522. ISBN: 0166-3615.
- [72] Daft, R. L., *Organization Theory and Design*. 2009, Mason, USA: South-Western Pub. ISBN: 978-0-324-59889-6.
- [73] Møller, C., *Erp Ii: A Conceptual Framework for Next-Generation Enterprise Systems?* Journal of Enterprise Information Management, 2005. 18(4): p. 483-497. ISBN: 1741-0398.
- [74] Hamilton, S., *Maximizing Your Erp System: A Practical Guide for Managers*. 2003, New York: McGraw-Hill Companies. ISBN: 0071406115.
- [75] Günther, H. O., *Supply Chain Management and Advanced Planning Systems: A Tutorial*. Supply Chain Management und Logistik, 2005: p. 3-40.
- [76] Barman, A. G., Bhattacharya, R., and Deb, S. K., *Strategic Initiatives and Automated Decision Support with Erp System Environment*. Information Processing and Management, 2010: p. 629-635.
- [77] Rudberg, M. and Thulin, J., *Centralised Supply Chain Master Planning Employing Advanced Planning Systems*. Production Planning & Control, 2009. 20(2): p. 158-167. ISBN: 0953-7287.
- [78] Meyr, H., Wagner, M., and Rohde, J., *Structure of Advanced Planning Systems*. Supply chain management and advanced planning, 2005: p. 109-115.
- [79] Kreipl, S. and Dickersbach, J. T., *Scheduling Coordination Problems in Supply Chain Planning*. Annals of Operations Research, 2008. 161(1): p. 103-122. ISBN: 0254-5330.
- [80] Chase, C., *Demand-Driven Forecasting: A Structured Approach to Forecasting*. 2009, New Jersey: John Wiley & Sons. ISBN: 978-0-470-41502-3.

- [81] Sayed, H. E., Gabbar, H. A., and Miyazaki, S., *A Hybrid Statistical Genetic-Based Demand Forecasting Expert System*. Expert Systems with Applications, 2009. 36(9): p. 11662-11670. ISBN: 0957-4174.
- [82] Carbonneau, R., Laframboise, K., and Vahidov, R., *Application of Machine Learning Techniques for Supply Chain Demand Forecasting*. European Journal of Operational Research, 2008. 184(3): p. 1140-1154. ISBN: 0377-2217.
- [83] Efendigil, T., Önüt, S., and Kahraman, C., *A Decision Support System for Demand Forecasting with Artificial Neural Networks and Neuro-Fuzzy Models: A Comparative Analysis*. Expert Systems with Applications, 2009. 36(3): p. 6697-6707. ISBN: 0957-4174.
- [84] Gutierrez, R. S., Solis, A. O., and Mukhopadhyay, S., *Lumpy Demand Forecasting Using Neural Networks*. International Journal of Production Economics, 2008. 111(2): p. 409-420. ISBN: 0925-5273.
- [85] Deng, W., Li, W., and Yang, X., *A Novel Hybrid Methodology of Bp Neural Network and Rough Set for Railway Passenger Traffic Demand Forecasting*. Expert Systems with Applications, 2010. ISBN: 0957-4174.
- [86] Pinedo, M., *Scheduling: Theory, Algorithms, and Systems*. 2008, New York: Springer-Verlag. ISBN: 978-0-387-78934-7.
- [87] Rekersbrink, H., Makuschewitz, T., and Scholz-Reiter, B., *A Distributed Routing Concept for Vehicle Routing Problems*. Logistics Research, 2009. 1(1): p. 45-52. ISBN: 1865-035X.
- [88] Stadtler, H., *A Framework for Collaborative Planning and State-of-the-Art*. Or Spectrum, 2009. 31(1): p. 5-30. ISBN: 0171-6468.
- [89] Stadtler, H., *Supply Chain Management and Advanced Planning--Basics, Overview and Challenges*. European Journal of Operational Research, 2005. 163(3): p. 575-588. ISBN: 0377-2217.
- [90] Caridi, M. and Sianesi, A. *Scm-Erp Integration: Organisational, Managerial and Technological Issues*. 2000: Citeseer.
- [91] Entrup, M. L., *Advanced Planning in Fresh Food Industries: Integrating Shelf Life into Production Planning*, ed. Müller, W. A. and Bihn, M. 2005, Heidelberg New York: Springer-Verlag. ISBN: 3790815926.
- [92] Moeslinger, C., Schmickl, T., Crailsheim, K., Kampis, G., Karsai, I. N., and Szathmáry, E. R., *A Minimalist Flocking Algorithm for Swarm Robots*. *Advances in Artificial Life. Darwin Meets Von Neumann*. 2011, Springer Berlin / Heidelberg. p. 375-382. DOI: 10.1007/978-3-642-21314-4_47. ISBN: 978-3-642-21313-7.
- [93] Yoon, S. W. and Nof, S. Y., *Demand and Capacity Sharing Decisions and Protocols in a Collaborative Network of Enterprises*. Decision Support Systems, 2010. 49(4): p. 442-450. ISBN: 0167-9236.
- [94] Li, S., Ragu-Nathan, B., Ragu-Nathan, T., and Subba Rao, S., *The Impact of Supply Chain Management Practices on Competitive Advantage and Organizational Performance*. Omega, 2006. 34(2): p. 107-124. ISBN: 0305-0483.
- [95] Cooper, M. C., Lambert, D. M., and Pagh, J. D., *Supply Chain Management: More Than a New Name for Logistics*. International Journal of Logistics Management, The, 1997. 8(1): p. 1-14. ISBN: 0957-4093.
- [96] Coyle, J. J., Langley, C. J., Bardi, E. J., Gibson, B. J., and Novack, R. A., *Supply Chain Management: A Logistics Perspective*. 2008: South-Western Pub. ISBN: 0324224338.
- [97] Harrison, A. and Van Hoek, R. I., *Logistics Management and Strategy: Competing through the Supply Chain*. 2008: Prentice Hall. ISBN: 0273712764.
- [98] Tan, K. C., *A Framework of Supply Chain Management Literature*. European Journal of Purchasing & Supply Management, 2001. 7(1): p. 39-48. ISBN: 0969-7012.
- [99] Monczka, R. M., Handfield, R. B., Guinipero, L., Patterson, J. L., and Walters, D., *Purchasing and Supply Chain Management*. 2010, Singapore: Cengage Learning EMEA. ISBN: 978-1-4080-1744-9.
- [100] Ben Naylor, J., Naim, M. M., and Berry, D., *Leagility: Integrating the Lean and Agile Manufacturing Paradigms in the Total Supply Chain*. International Journal of Production Economics, 1999. 62(1-2): p. 107-118. ISBN: 0925-5273.

- [101] Moyaux, T., Chaib-Draa, B., and D'amours, S. *Multi-Agent Simulation of Collaborative Strategies in a Supply Chain*. In the Third International Joint Conference on Autonomous Agents and Multiagent Systems. 2004. New York: IEEE Computer Society. DOI: <http://dx.doi.org/10.1109/AAMAS.2004.184>. ISBN: 1-58113-864-4.
- [102] Sabri, E. H. and Shaikh, S. N., *Lean and Agile Value Chain Management: A Guide to the Next Level of Improvement*. 2009: J. Ross Publishing. ISBN: 978-1-60427-025-9.
- [103] Tian, Y., *Automotive Supply Chain Evaluation with Conventional Model and Integrated Model*, in *Maschinenbau und Verfahrenstechni*. 2011, Universität Duisburg-Essen: Duisburg-Essen.
- [104] Rogalski, S., *Flexibility Measurement in Production Systems: Handling Uncertainties in Industrial Production*. 2011: Springer. ISBN: 3642181163.
- [105] Koren, Y., *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*. vol. 75. 2010, New Jersey: John Wiley & Sons. ISBN: 978-0-470-58377-7.
- [106] Yang, B., Burns, N. D., and Backhouse, C. J., *Management of Uncertainty through Postponement*. International Journal of Production Research, 2004. 42(6): p. 1049-1064. ISBN: 0020-7543.
- [107] Sudo, Y., Sakao, N., and Matsuda, M., *An Agent Behavior Technique in an Autonomous Decentralized Manufacturing System*. Journal of Advanced Mechanical Design, Systems, and Manufacturing, 2010. 4(3): p. 673-682. ISBN: 1881-3054.
- [108] Windt, K., Becker, T., Jeken, O., and Gelessus, A., *A Classification Pattern for Autonomous Control Methods in Logistics*. Logistics Research, 2010: p. 1-12. ISBN: 1865-035X.
- [109] Duffie, N. A. and Shi, L., *Dynamics of Wip Regulation in Large Production Networks of Autonomous Work Systems*. Automation Science and Engineering, IEEE Transactions on, 2010. 7(3): p. 665-670. ISBN: 1545-5955.
- [110] Scholz-Reiter, B., Windt, K., and Freitag, M. *Autonomous Logistic Processes: New Demands and First Approaches*. In 37th CIRP International Seminar on Manufacturing Systems. 2004. Budapest, Hungaria: Citeseer.
- [111] Romano, P., *Co-Ordination and Integration Mechanisms to Manage Logistics Processes across Supply Networks*. Purchasing & Supply Management, 2003. 9: p. 119-134.
- [112] Onlinedictionary, *System*. 2011, BusinessDictionary.
- [113] Zhang, D., Lowry, P. B., Zhou, L., and Fu, X., *The Impact of Individualism—Collectivism, Social Presence, and Group Diversity on Group Decision Making under Majority Influence*. Journal of Management Information Systems, 2007. 23(4): p. 53-80. ISBN: 0742-1222.
- [114] Van De Mortel-Fronczak, J., Schmitz, J., and Rooda, J. *Experimental Comparison of Control Architectures*. In APMS. 1999.
- [115] Van Dongen, J., Van De Mortel-Fronczak, J., and Rooda, J., *Heterarchical Control of a Lithoshop*. Master's thesis. Eindhoven University of Technology, Department of Mechanical Engineering. Eindhoven, the Netherlands, 1998.
- [116] Jafari, A. M. M., *Development and Evaluation of an Autonomous Wireless Sensor Actuator Network in Logistic Systems*. 2010, Bremen University.
- [117] Rupp, B., Okelberry, R., Wipful, R., and Jones, R., *Method for Consensus Decision Making in a Distributed System*. 2009, Google Patents.
- [118] Kurokawa, H., Tomita, K., Kamimura, A., Kokaji, S., Hasuo, T., and Murata, S., *Distributed Self-Reconfiguration of M-Tran Iii Modular Robotic System*. The International Journal of Robotics Research, 2008. 27(3-4): p. 373. ISBN: 0278-3649.
- [119] Matsumoto, A., Asama, H., Ishida, Y., Ozaki, K., and Endo, I. *Communication in the Autonomous and Decentralized Robot System Actress*. In Proceedings. IROS '90. IEEE International Workshop on Intelligent Robots and Systems '90. 'Towards a New Frontier of Applications'. 1990. Ibaraki, Japan IEEE. DOI: 10.1109/IROS.1990.262503
- [120] Ahituv, N., Neumann, S., and Zviran, M., *Factors Affecting the Policy for Distributing Computing Resources*. MIS Quarterly, 1989. 13(4): p. 389-401. ISBN: 0276-7783.
- [121] Kumar, R. and Takai, S., *Inference-Based Ambiguity Management in Decentralized Decision-Making: Decentralized Diagnosis of Discrete-Event Systems*. Automation Science and Engineering, IEEE Transactions on, 2009. 6(3): p. 479-491. ISBN: 1545-5955.

- [122] Meyer, R. E. and Hammerschmid, G., *The Degree of Decentralization and Individual Decision Making in Central Government Human Resource Management: A European Comparative Perspective*. Public Administration, 2010. 88(2): p. 455-478. ISBN: 1467-9299.
- [123] Eymann, T., Reinicke, M., Ardaiz, O., Artigas, P., Diaz De Cerio, L., Freitag, F., Messeguer, R., Navarro, L., Royo, D., and Sanjeevan, K. *Decentralized Vs. Centralized Economic Coordination of Resource Allocation in Grids*. 2004: Springer.
- [124] Rehtanz, C., *Autonomous Systems and Intelligent Agents in Power System Control and Operation*. 2003: Springer Verlag. ISBN: 3540402020.
- [125] Scholz-Reiter, B., Kolditz, J., and Hildebrandt, T., *Specifying Adaptive Business Processes within the Production Logistics Domain—a New Modelling Concept and Its Challenges*. In Understanding Autonomous Cooperation and Control in Logistics: The Impact of Autonomy on Management, Information, Communication and Material Flow, Hülsmann, M. and Windt, K., Editors. 2007, Springer-Verlag: Berlin Heidelberg New York. p. 275. ISBN: 978-3-540-47449-4.
- [126] Scholz-Reiter, B., Freitag, M., De Beer, C., and Jagalski, T. *Analysing the Dynamics Caused by Autonomously Controlled Logistic Objects*. In Int. Conf. on Changeable, Agile, Reconfigurable and Virtual Production. 2007. University of Windsor: Citeseer.
- [127] Duffie, N. A., Prabhu, V. V., and Kaltjob, P. O., *Closed-Loop Real-Time Cooperative Decision-Making Dynamics in Heterarchical Manufacturing Systems*. Journal of manufacturing systems, 2002. 21(6): p. 409-418. ISBN: 0278-6125.
- [128] Schuldt, A., *Multiagent Coordination Enabling Autonomous Logistics*. 2011, Heidelberg, Germany: Springer-Verlag. ISBN: 978-3-642-20091-5.
- [129] Scholz-Reiter, B., Sowade, S., Hildebrandt, T., and Rippel, D., *Modeling of Orders in Autonomously Controlled Logistic Systems*. Production Engineering, 2010: p. 1-7. ISBN: 0944-6524.
- [130] Beck, U. and Beck-Gernsheim, E., *Individualization: Institutionalized Individualism and Its Social and Political Consequences*. vol. 13. 2002: Sage Publications Ltd. ISBN: 0761961127.
- [131] Pfister, C., *Getting Started with the Internet of Things*. 1st ed. ed, ed. Jepson, B. 2011, California, USA: O'Reilly Media. ISBN: 978-1-4493-9357-1.
- [132] Uckelmann, D., Harrison, M., and Michahelles, F., *Architecting the Internet of Things*. 2010, New York: Springer-Verlag DOI: 10.1007/978-3-642-19157-2. ISBN: 978-3-642-19156-5.
- [133] Kopetz, H., *Real-Time Systems: Design Principles for Distributed Embedded Applications*. 2nd ed. ed. 2011, New York: Springer-Verlag DOI: 10.1007/978-1-4419-8237-7. ISBN: 978-1-4419-8236-0.
- [134] Poluha, R. G., *Application of the Scor Model in Supply Chain Management*. 2007: Cambria Pr. ISBN: 978-1-1934043-23-3.
- [135] Olhager, J., *The Role of the Customer Order Decoupling Point in Production and Supply Chain Management*. Computers in industry, 2010. ISBN: 0166-3615.
- [136] Persson, F. and Araldi, M., *The Development of a Dynamic Supply Chain Analysis Tool--Integration of Scor and Discrete Event Simulation*. International Journal of Production Economics, 2009. 121(2): p. 574-583. ISBN: 0925-5273.
- [137] Gosling, J. and Naim, M. M., *Engineer-to-Order Supply Chain Management: A Literature Review and Research Agenda*. International Journal of Production Economics, 2009. 122(2): p. 741-754. ISBN: 0925-5273.
- [138] Persson, F., *Scor Template-a Simulation Based Dynamic Supply Chain Analysis Tool*. International Journal of Production Economics, 2010. ISBN: 0925-5273.
- [139] Verdouw, C., Beulens, A., Trienekens, J., and Verwaart, T., *Towards Dynamic Reference Information Models: Readiness for Ict Mass Customisation*. Computers in industry, 2010. ISBN: 0166-3615.
- [140] Chan, F. T. S., Kumar, V., and Tiwari, M. K., *The Relevance of Outsourcing and Leagile Strategies in Performance Optimization of an Integrated Process Planning and Scheduling*. International Journal of Production Research, 2009. 47(1): p. 119-142. ISBN: 1366-588X.

- [141] Pavnaskar, S., Gershenson, J., and Jambekar, A., *Classification Scheme for Lean Manufacturing Tools*. International Journal of Production Research, 2003. 41(13): p. 3075-3090. ISBN: 0020-7543.
- [142] Narasimhan, R., Swink, M., and Kim, S. W., *Disentangling Leanness and Agility: An Empirical Investigation*. Journal of Operations Management, 2006. 24(5): p. 440-457. ISBN: 0272-6963.
- [143] Shah, R. and Ward, P. T., *Lean Manufacturing: Context, Practice Bundles, and Performance*. Journal of Operations Management, 2003. 21(2): p. 129-149. ISBN: 0272-6963.
- [144] Alford, D., Sackett, P., and Nelder, G., *Mass Customisation--an Automotive Perspective*. International Journal of Production Economics, 2000. 65(1): p. 99-110. ISBN: 0925-5273.
- [145] Powell, D., Alfnes, E., and Semini, M., *The Application of Lean Production Control Methods within a Process-Type Industry: The Case of Hydro Automotive Structures*. Advances in Production Management Systems. New Challenges, New Approaches, 2010: p. 243-250.
- [146] James-Moore, S. and Gibbons, A., *Is Lean Manufacture Universally Relevant? An Investigative Methodology*. International Journal of Operations & Production Management, 1997. 17(9): p. 899-911. ISBN: 0144-3577.
- [147] Jina, J., Bhattacharya, A. K., and Walton, A. D., *Applying Lean Principles for High Product Variety and Low Volumes: Some Issues and Propositions*. Logistics Information Management, 1997. 10(1): p. 5-13. ISBN: 0957-6053.
- [148] Nagel, R. N., Dove, R., Goldham, S., and Preiss, K., *21st Century Manufacturing Enterprise Strategy*. vol. 2. 1991: Iacocca Institute, Lehigh University. ISBN: 0962486639.
- [149] Hallgren, M. and Olhager, J., *Lean and Agile Manufacturing: External and Internal Drivers and Performance Outcomes*. International Journal of Operations & Production Management, 2009. 29(10): p. 976-999. ISBN: 0144-3577.
- [150] Sharifi, H. and Zhang, Z., *Agile Manufacturing in Practice-Application of a Methodology*. International Journal of Operations & Production Management, 2001. 21(5/6): p. 772-794. ISBN: 0144-3577.
- [151] Barker, J. and Finnie, G., *The Next Generation Demand Network in Quick Response Systems: Intelligent Products, Packet Switching and Dynamic Information*. Innovative Quick Response Programs in Logistics and Supply Chain Management, 2010: p. 243-263.
- [152] Flocchini, P., Prencipe, G., Santoro, N., and Widmayer, P., *Distributed Coordination of a Set of Autonomous Mobile Robots*. 2000: IEEE. ISBN: 0780363639.
- [153] Frazzoli, E., Dahleh, M. A., and Feron, E., *Real-Time Motion Planning for Agile Autonomous Vehicles*. JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS, 2002. 25(1): p. 116-129.
- [154] Van Hoek, R. I., Harrison, A., and Christopher, M., *Measuring Agile Capabilities in the Supply Chain*. International Journal of Operations & Production Management, 2001. 21(1/2): p. 126-148. ISBN: 0144-3577.
- [155] Scholten, K., Scott, P. S., and Fynes, B., *(Le) Agility in Humanitarian Aid (Ngo) Supply Chains*. International Journal of Physical Distribution & Logistics Management, 2010. 40(8/9): p. 623-635. ISBN: 0960-0035.
- [156] Krishnamurthy, R. and Yauch, C. A., *Leagile Manufacturing: A Proposed Corporate Infrastructure*. International Journal of Operations & Production Management, 2007. 27(6): p. 588-604. ISBN: 0144-3577.
- [157] Mason-Jones, R., Naylor, B., and Towill, D. R., *Engineering the Leagile Supply Chain*. International Journal of Agile Management Systems, 2000. 2(1): p. 54-61. ISBN: 1465-4652.
- [158] Christopher, M. and Towill, D. R., *Supply Chain Migration from Lean and Functional to Agile and Customised*. Supply Chain Management: An International Journal, 2000. 5(4): p. 206-213. ISBN: 1359-8546.
- [159] Haug, A., Ladeby, K., and Edwards, K., *From Engineer-to-Order to Mass Customization*. Management Research News, 2009. 32(7): p. 633-644. ISBN: 0140-9174.
- [160] Scholz-Reiter, B. and Mehraei, A., *Integration of Lean-Agile Experiments with Autonomy in Supply Chains*. In Proc. of the 7th International Conference on Manufacturing Research (ICMR09). 2009. Warwick, England: University of Warwick.

- [161] Trentin, A., Salvador, F., Forza, C., and Rungtusanatham, M. J., *Operationalising Form Postponement from a Decision-Making Perspective*. International Journal of Production Research, 2011. 49(7): p. 1977-1999. ISBN: 0020-7543.
- [162] Davis, S. M., *From "Future Perfect": Mass Customizing*. Strategy & Leadership, 1989. 17(2): p. 16-21. ISBN: 1087-8572.
- [163] Liu, G. J. and Deitz, G. D., *Linking Supply Chain Management with Mass Customization Capability*. International Journal of Physical Distribution & Logistics Management, 2011. 41(7): p. 2-2. ISBN: 0960-0035.
- [164] Zipkin, P., *The Limits of Mass Customization*. Harvard Business Review, 1997. 75: p. 91-101. ISBN: 1532-9194.
- [165] Zhang, L. L., Lee, C. K. M., and Xu, Q., *Towards Product Customization: An Integrated Order Fulfillment System*. Computers in industry, 2009. 61(3): p. 213-222. ISBN: 0166-3615.
- [166] Brabazon, P. G., Maccarthy, B., Woodcock, A., and Hawkins, R. W., *Mass Customization in the Automotive Industry: Comparing Interdealer Trading and Reconfiguration Flexibilities in Order Fulfillment*. Production and Operations Management, 2010. 19(5): p. 489-502. ISBN: 1937-5956.
- [167] Karpowitz, D. J., Cox, J. J., Humpherys, J. C., and Warnick, S. C., *A Dynamic Workflow Framework for Mass Customization Using Web Service and Autonomous Agent Techniques*. Journal of Intelligent Manufacturing, 2008. 19(5): p. 537-552. ISBN: 0956-5515.
- [168] Gehrke, J. D., Herzog, O., Langer, H., Malaka, R., Porzel, R., and Warden, T., *An Agent-Based Approach to Autonomous Logistic Processes*. KI-Künstliche Intelligenz, 2010: p. 1-5. ISBN: 0933-1875.
- [169] Salvador, F., Rungtusanatham, M., Forza, C., and Trentin, A., *Mix Flexibility and Volume Flexibility in a Build-to-Order Environment: Synergies and Trade-Offs*. International Journal of Operations & Production Management, 2007. 27(11): p. 1173-1191. ISBN: 0144-3577.
- [170] Tseng, M. M. and Jiao, J., *Mass Customization*. Handbook of Industrial Engineering, 3rd edition, New York: Wiley, 2001: p. 684-709.
- [171] Monfared, M. A. S. and Yang, J., *Design of Integrated Manufacturing Planning, Scheduling and Control Systems: A New Framework for Automation*. The International Journal of Advanced Manufacturing Technology, 2007. 33(5): p. 545-559. ISBN: 0268-3768.
- [172] Moon, C., Lee, Y. H., Jeong, C. S., and Yun, Y. S., *Integrated Process Planning and Scheduling in a Supply Chain*. Computers & industrial engineering, 2008. 54(4): p. 1048-1061. ISBN: 0360-8352.
- [173] Pinedo, M. L., *Planning and Scheduling in Manufacturing and Services*. 2009, Heidelberg London New York: Springer-Verlag. ISBN: 978-1-4419-0909-1.
- [174] Brucker, P., *Scheduling Algorithms*. 2007, Berlin Heidelberg New York: Springer-Verlag. ISBN: 354069515-8.
- [175] Mehraei, A., Scholz-Reiter, B., and Wenning, B. L. *Analysis of Learning Pallets in Flexible Scheduling by Closed Queue Network*. In Assembly and Manufacturing (ISAM), 2011 IEEE International Symposium on. 2011. Tampere: IEEEExplore. DOI: 10.1109/ISAM.2011.5942357 ISBN: 978-1-61284-342-1
- [176] Mehraei, A. and Scholz-Reiter, B. *Application of Learning Pallets in Hybrid Flow-Open Shop Scheduling, Using Artificial Intelligence*. In The 44th CIRP Conference on Manufacturing Systems. 2011. Madison, USA: CIRP.
- [177] Blazewicz, J., Lenstra, J. K., and Kan, A., *Scheduling Subject to Resource Constraints: Classification and Complexity*. Discrete Applied Mathematics, 1983. 5(1): p. 11-24. ISBN: 0166-218X.
- [178] Allahverdi, A., Ng, C., Cheng, T., and Kovalyov, M. Y., *A Survey of Scheduling Problems with Setup Times or Costs*. European Journal of Operational Research, 2008. 187(3): p. 985-1032. ISBN: 0377-2217.
- [179] Sakawa, M. and Kubota, R., *Fuzzy Programming for Multiobjective Job Shop Scheduling with Fuzzy Processing Time and Fuzzy Due date through Genetic Algorithms*. European Journal of Operational Research, 2000. 120(2): p. 393-407. ISBN: 0377-2217.

- [180] Frantzen, M., Ng, A. H. C., and Moore, P., *A Simulation-Based Scheduling System for Real-Time Optimization and Decision Making Support*. Robotics and Computer-Integrated Manufacturing, 2011. 27(4): p. 696-705. DOI: 10.1016/j.rcim.2010.12.006. ISBN: 0736-5845.
- [181] Essafi, I., Mati, Y., and Dauzère-Pérès, S., *A Genetic Local Search Algorithm for Minimizing Total Weighted Tardiness in the Job-Shop Scheduling Problem*. Computers & Operations Research, 2008. 35(8): p. 2599-2616. ISBN: 0305-0548.
- [182] Mahdavinejad, R. A., *Job Shop-Scheduling Problems-Single Process*. Applied Mechanics and Materials, 2011. 44: p. 330-334. ISBN: 1662-7482.
- [183] Noori-Darvish, S. and Tavakkoli-Moghaddam, R., *Solving a Bi-Objective Open Shop Scheduling Problem with Fuzzy Parameters*. Journal of Applied Operational Research, 2011. 3(2): p. 59-74.
- [184] Pezzella, F., Morganti, G., and Ciaschetti, G., *A Genetic Algorithm for the Flexible Job-Shop Scheduling Problem*. Computers & Operations Research, 2008. 35(10): p. 3202-3212. ISBN: 0305-0548.
- [185] Ochoa, G., Vázquez-Rodríguez, J. A., Petrovic, S., and Burke, E., *Dispatching Rules for Production Scheduling: A Hyper-Heuristic Landscape Analysis*. In IEEE Congress on Evolutionary Computation, 2009. CEC '09. 2009: IEEEExplore. DOI: 10.1109/CEC.2009.4983169 ISBN: 978-1-4244-2958-5
- [186] Alumur, S. and Kara, B. Y., *Network Hub Location Problems: The State of the Art*. European Journal of Operational Research, 2008. 190(1): p. 1-21. ISBN: 0377-2217.
- [187] Oey, K. and Mason, S. J., *Scheduling and Dispatching: Scheduling Batch Processing Machines in Complex Job Shops*. 2001: IEEE Computer Society. ISBN: 078037309X.
- [188] Sexton, R. S., Dorsey, R. E., and Johnson, J. D., *Toward Global Optimization of Neural Networks: A Comparison of the Genetic Algorithm and Backpropagation*. Decision Support Systems, 1998. 22(2): p. 171-185. ISBN: 0167-9236.
- [189] Kao, Y. T. and Zahara, E., *A Hybrid Genetic Algorithm and Particle Swarm Optimization for Multimodal Functions*. Applied Soft Computing, 2008. 8(2): p. 849-857. ISBN: 1568-4946.
- [190] Yu, W., Liu, Z., Wang, L., and Fan, T., *Routing Open Shop and Flow Shop Scheduling Problems*. European Journal of Operational Research, 2011. 213(1): p. 24-36 DOI: 10.1016/j.ejor.2011.02.028 ISBN: 0377-2217.
- [191] Ham, M., Lee, Y. H., and Kim, S. H., *Real-Time Scheduling of Multi-Stage Flexible Job Shop Floor*. International Journal of Production Research, 2011. 49(12): p. 3715-3730. ISBN: 0020-7543.
- [192] Lin, T. L., Horng, S. J., Kao, T. W., Chen, Y. H., Run, R. S., Chen, R. J., Lai, J. L., and Kuo, I., *An Efficient Job-Shop Scheduling Algorithm Based on Particle Swarm Optimization*. Expert Systems with Applications, 2010. 37(3): p. 2629-2636. ISBN: 0957-4174.
- [193] Sha, D. and Hsu, C. Y., *A New Particle Swarm Optimization for the Open Shop Scheduling Problem*. Computers & Operations Research, 2008. 35(10): p. 3243-3261. ISBN: 0305-0548.
- [194] Isovie, D., *Handling Sporadic Tasks in Real-Time Systems: Combined Offline and Online Approach*, in *Department of Computer Engineering*. 2001, Mälardalen University: Mälardalen, Sweden. ISBN: 9188834204.
- [195] Sabuncuoglu, I. and Bayiz, M., *Analysis of Reactive Scheduling Problems in a Job Shop Environment*. European Journal of Operational Research, 2000. 126(3): p. 567-586. ISBN: 0377-2217.
- [196] Cowling, P. and Johansson, M., *Using Real Time Information for Effective Dynamic Scheduling*. European Journal of Operational Research, 2002. 139(2): p. 230-244. ISBN: 0377-2217.
- [197] Choi, H., Kim, J., and Lee, D., *Real-Time Scheduling for Reentrant Hybrid Flow Shops: A Decision Tree Based Mechanism and Its Application to a Tft-Lcd Line*. Expert Systems with Applications, 2010. ISBN: 0957-4174.
- [198] Lu, C., Stankovic, J. A., Son, S. H., and Tao, G., *Feedback Control Real-Time Scheduling: Framework, Modeling, and Algorithms**. Real-Time Systems, 2002. 23(1): p. 85-126. ISBN: 0922-6443.

- [199] Ben Gaid, M. E. M., Çela, A. S., and Hamam, Y., *Optimal Real-Time Scheduling of Control Tasks with State Feedback Resource Allocation*. Control Systems Technology, IEEE Transactions on, 2009. 17(2): p. 309-326. ISBN: 1063-6536.
- [200] Savkin, A. V. and Somlo, J., *Optimal Distributed Real-Time Scheduling of Flexible Manufacturing Networks Modeled as Hybrid Dynamical Systems*. Robotics and Computer-Integrated Manufacturing, 2009. 25(3): p. 597-609. ISBN: 0736-5845.
- [201] Huang, G. Q., Zhang, Y., and Jiang, P., *Rfid-Based Wireless Manufacturing for Real-Time Management of Job Shop Wip Inventories*. The International Journal of Advanced Manufacturing Technology, 2008. 36(7): p. 752-764. ISBN: 0268-3768.
- [202] Kim, J. H. and Duffie, N. A., *Design and Analysis of Closed-Loop Capacity Control for a Multi-Workstation Production System*. Cirp Annals-Manufacturing Technology, 2005. 54(1): p. 455-458. ISBN: 0007-8506.
- [203] Helber, S., Schimmelpfeng, K., and Stolletz, R., *Setting Inventory Levels of Conwip Flow Lines Via Linear Programming*. Diskussionspapiere der Wirtschaftswissenschaftlichen Fakultät der Universität Hannover, 2009.
- [204] Kannan, G., Sasikumar, P., and Devika, K., *A Genetic Algorithm Approach for Solving a Closed Loop Supply Chain Model: A Case of Battery Recycling*. Applied Mathematical Modelling, 2010. 34(3): p. 655-670. ISBN: 0307-904X.
- [205] Wang, H. F. and Hsu, H. W., *A Closed-Loop Logistic Model with a Spanning-Tree Based Genetic Algorithm*. Computers & Operations Research, 2010. 37(2): p. 376-389. ISBN: 0305-0548.
- [206] Yang, G., Wang, Z., and Li, X., *The Optimization of the Closed-Loop Supply Chain Network*. Transportation Research Part E: Logistics and Transportation Review, 2009. 45(1): p. 16-28. ISBN: 1366-5545.
- [207] Shi, J., Zhang, G., and Sha, J., *Optimal Production Planning for a Multi-Product Closed Loop System with Uncertain Demand and Return*. Computers & Operations Research, 2010. ISBN: 0305-0548.
- [208] Gupta, A. and Maranas, C., *Managing Demand Uncertainty in Supply Chain Planning*. Computers & Chemical Engineering, 2003. 27(8-9): p. 1219-1227.
- [209] Sevastjanov, P. and Rog, P., *Fuzzy Modeling of Manufacturing and Logistic Systems*. Mathematics and Computers in Simulation, 2003. 63(6): p. 569-585.
- [210] Mula, J., Poler, R., Garcia-Sabater, J., and Lario, F., *Models for Production Planning under Uncertainty: A Review*. International Journal of Production Economics, 2006. 103(1): p. 271-285.
- [211] Bozarth, C. C., Warsing, D. P., Flynn, B. B., and Flynn, E. J., *The Impact of Supply Chain Complexity on Manufacturing Plant Performance*. Journal of Operations Management, 2009. 27(1): p. 78-93. ISBN: 0272-6963.
- [212] Lin, J. T., Chen, T. L., and Lin, Y. T., *Critical Material Planning for Tft-Lcd Production Industry*. International Journal of Production Economics, 2009. 122(2): p. 639-655. ISBN: 0925-5273.
- [213] Cheng, J. C. P., Law, K. H., Bjornsson, H., Jones, A., and Sriram, R. D., *Modeling and Monitoring of Construction Supply Chains*. Advanced Engineering Informatics, 2010. ISBN: 1474-0346.
- [214] Jain, V. and Deshmukh, S., *Dynamic Supply Chain Modeling Using a New Fuzzy Hybrid Negotiation Mechanism*. International Journal of Production Economics, 2009. 122(1): p. 319-328. ISBN: 0925-5273.
- [215] Becker, T., Beber, M. E., Windt, K., Hütt, M. T., and Helbing, D., *Flow Control by Periodic Devices: A Unifying Language for the Description of Traffic, Production, and Metabolic Systems*. Journal of Statistical Mechanics: Theory and Experiment, 2011. 2011. DOI: 10.1088/1742-5468/2011/05/P05004.
- [216] Li, X. and Marlin, T. E., *Robust Supply Chain Performance Via Model Predictive Control*. Computers & Chemical Engineering, 2009. 33(12): p. 2134-2143. ISBN: 0098-1354.
- [217] Nagy, Z. and Braatz, R., *Open-Loop and Closed-Loop Robust Optimal Control of Batch Processes Using Distributional and Worst-Case Analysis*. Journal of process control, 2004. 14(4): p. 411-422.
- [218] Kogan, K., *Production Control under Uncertainty: Closed-Loop Versus Open-Loop Approach*. IIE Transactions, 2009. 41(10): p. 905-915. ISBN: 0740-817X.

- [219] Krishnamurthy, A., Suri, R., and Vernon, M. *A New Approach for Analyzing Queueing Models of Material Control Strategies in Manufacturing Systems*. 2000: Citeseer.
- [220] Duenyas, I. and Hopp, W. J., *Estimating Variance of Output from Cyclic Exponential Queueing Systems*. Queueing Systems, 1990. 7(3): p. 337-353. ISBN: 0257-0130.
- [221] Levantesi, R., *Analysis of Multiple Loop Assembly/Disassembly Networks*. 2001, Politecnico di Milano.
- [222] Gershwin, S. and Werner, L., *An Approximate Analytical Method for Evaluating the Performance of Closed-Loop Flow Systems with Unreliable Machines and Finite Buffers*. International Journal of Production Research, 2007. 45(14): p. 3085-3112.
- [223] Helber, S. S., Katja & Stollatz, Raik, *Setting Inventory Levels of Conwip Flow Lines Via Linear Programming*, . BuR Business Research, 2011. 4(1): p. 98-115.
- [224] Ip, W., Huang, M., Yung, K., Wang, D., and Wang, X., *Conwip Based Control of a Lamp Assembly Production Line*. Journal of Intelligent Manufacturing, 2007. 18(2): p. 261-271. ISBN: 0956-5515.
- [225] Li, N., Zheng, L., and Li, Q. L., *Performance Analysis of Two-Loop Closed Production Systems*. Computers & Operations Research, 2009. 36(1): p. 119-134. ISBN: 0305-0548.
- [226] O'dell, T., *A Closed-Loop System for the Measurement of Self-Heating in Bjts*. Solid-State Electronics, 2004. 48(1): p. 167-170. ISBN: 0038-1101.
- [227] Borovic, B., Liu, A., Popa, D., Cai, H., and Lewis, F., *Open-Loop Versus Closed-Loop Control of Mems Devices: Choices and Issues*. Journal of Micromechanics and Microengineering, 2005. 15: p. 1917.
- [228] Olson, B. and Si, J., *Evidence of a Mechanism of Neural Adaptation in the Closed Loop Control of Directions*. International Journal of Intelligent Computing and Cybernetics, 2010. 3(1): p. 5-23. ISBN: 1756-378X.
- [229] Rowley, C. and Batten, B., *Dynamic and Closed-Loop Control*. In Fundamentals and Applications of Modern Flow Control,, R. D. Joslin and D. N. Miller, Editor. September 2009, AIAA Progress in Astronautics and Aeronautics. p. 115-148,.
- [230] Gao, H. and Chen, T., *A New Approach to Quantized Feedback Control Systems*. Automatica, 2008. 44(2): p. 534-542. ISBN: 0005-1098.
- [231] Jansson, H. and Hjalmarsson, H. *From Open-Loop Learning to Closed-Loop Control*. In Proceedings of the 41st IEEE Conference on Decision and Control, 2002. 2002: IEEEExplore. DOI: 10.1109/CDC.2002.1185030 ISBN: 0-7803-7516-5
- [232] Kulvicius, T., Kolodziejski, C., Tamosiunaite, M., Porr, B., and Wörgötter, F., *Behavioral Analysis of Differential Hebbian Learning in Closed-Loop Systems*. Biological Cybernetics, 2010: p. 255-271. DOI: 10.1007/s00422-010-0396-4.
- [233] Dorigo, M. and Colombetti, M., *Robot Shaping: Developing Autonomous Agents through Learning*. Artificial intelligence, 1994. 71(2): p. 321-370. DOI: 71:321-370. ISBN: 0004-3702.
- [234] Andry, P., Gaussier, P., Moga, S., Banquet, J., and Nadel, J., *Learning and Communication Via Imitation: An Autonomous Robot Perspective*. IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART A: SYSTEMS AND HUMANS, 2001. 31(5): p. 431.
- [235] Mehraei, A., Teucke, M., and Scholz-Reiter, B., *Coordination of Push-Pull Principle Logistics Network by Optimizing Material-Pull; Applying Genetic Algorithm*. In Proceedings: The 1st International Conference on Logistics and Maritime Systems (LOGMS), 2010, Pusan., 2010: p. 2-11.
- [236] Pahl, J., Voss, S., and Woodruff, D. L., *Production Planning with Load Dependent Lead Times*. 4OR: A Quarterly Journal of Operations Research, 2005. 3(4): p. 257-302. ISBN: 1619-4500.
- [237] Fernandes, N. and Do Carmo-Silva, S., *Generic Polca--a Production and Materials Flow Control Mechanism for Quick Response Manufacturing*. International Journal of Production Economics, 2006. 104(1): p. 74-84.
- [238] Germs, R. and Riezebos, J., *Workload Balancing Capability of Pull Systems in Mto Production*. International Journal of Production Research, 2010. 48(08): p. 2345-2360.
- [239] Krishnamurthy, A., Suri, R., and Vernon, M., *Re-Examining the Performance of Mrp and Kanban Material Control Strategies for Multi-Product Flexible Manufacturing Systems*.

- International journal of flexible manufacturing systems, 2004. 16(2): p. 123-150. ISBN: 0920-6299.
- [240] Krishnamurthy, A. and Suri, R., *Planning and Implementing Polca: A Card-Based Control System for High Variety or Custom Engineered Products*. Production Planning & Control, 2009. 20(7): p. 596-610. ISBN: 0953-7287.
 - [241] Yucesan, E. and De Groote, X., *Lead Times, Order Release Mechanisms, and Customer Service*. European Journal of Operational Research, 2000. 120(1): p. 118-130. ISBN: 0377-2217.
 - [242] Spearman, M. L., Woodruff, D. L., and Hopp, W. J., *Conwip: A Pull Alternative to Kanban*. International Journal of Production Research, 1990. 28(5): p. 879-894. ISBN: 0020-7543.
 - [243] Sendil Kumar, C. and Panneerselvam, R., *Literature Review of Jit-Kanban System*. The International Journal of Advanced Manufacturing Technology, 2007. 32(3): p. 393-408. ISBN: 0268-3768.
 - [244] Matsui, Y., *An Empirical Analysis of Just-in-Time Production in Japanese Manufacturing Companies*. International Journal of Production Economics, 2007. 108(1-2): p. 153-164. ISBN: 0925-5273.
 - [245] Sihn, W. and Schmitz, K., *Extended Multi-Customer Supplier Parks in the Automotive Industry*. Cirp Annals-Manufacturing Technology, 2007. 56(1): p. 479-482. ISBN: 0007-8506.
 - [246] Guan, Z., Peng, Y., Ma, L., Zhang, C., and Li, P., *Operation and Control of Flow Manufacturing Based on Constraints Management for High-Mix/Low-Volume Production*. Frontiers of Mechanical Engineering in China, 2008. 3(4): p. 454-461. ISBN: 1673-3479.
 - [247] Ahmadi, R. H. and Matsuo, H., *A Mini-Line Approach for Pull Production*. European Journal of Operational Research, 2000. 125(2): p. 340-358. ISBN: 0377-2217.
 - [248] Fernandes, N. O. and Do Carmo-Silva, S., *Generic Polca--a Production and Materials Flow Control Mechanism for Quick Response Manufacturing*. International Journal of Production Economics, 2006. 104(1): p. 74-84. ISBN: 0925-5273.
 - [249] Lödding, H., Yu, K. W., and Wiendahl, H. P., *Decentralized Wip-Oriented Manufacturing Control (Dewip)*. Production Planning & Control, 2003. 14(1): p. 42-54. ISBN: 0953-7287.
 - [250] Lage Junior, M. and Godinho Filho, M., *Variations of the Kanban System: Literature Review and Classification*. International Journal of Production Economics, 2010. 125(1): p. 13-21. ISBN: 0925-5273.
 - [251] Miyashita, K. and Rajesh, G., *Multiagent Coordination for Controlling Complex and Unstable Manufacturing Processes*. Expert Systems with Applications, 2010. 37(3): p. 1836-1845. ISBN: 0957-4174.
 - [252] Suri, R., *Quick Response Manufacturing: A Companywide Approach to Reducing Lead Times*. 1998: Productivity Press. ISBN: 1-56327-201-6.
 - [253] Geraghty, J. and Heavey, C., *A Comparison of Hybrid Push/Pull and Conwip/Pull Production Inventory Control Policies*. International Journal of Production Economics, 2004. 91(1): p. 75-90. ISBN: 0925-5273.
 - [254] Thun, J. H., Drüke, M., and Grübner, A., *Empowering Kanban through Tps-Principles-an Empirical Analysis of the Toyota Production System*. International Journal of Production Research, 2010: p. 1. DOI: 10.1080/00207540903436695.
 - [255] Araz, O. U., Eski, O., and Araz, C., *Determining the Parameters of Dual-Card Kanban System: An Integrated Multicriteria and Artificial Neural Network Methodology*. The International Journal of Advanced Manufacturing Technology, 2008. 38(9): p. 965-977. ISBN: 0268-3768.
 - [256] Li, N., Yao, S., Liu, G., and Zhuang, C., *Optimization of a Multi-Constant Work-in-Process Semiconductor Assembly and Test Factory Based on Performance Evaluation*. Computers & industrial engineering, 2010. ISBN: 0360-8352.
 - [257] Takahashi, K., *Comparing Conwip, Synchronized Conwip, and Kanban in Complex Supply Chains*. International Journal of Production Economics, 2005. 93: p. 25-40. ISBN: 0925-5273.
 - [258] Lu, J. C., Yang, T., and Wang, C. Y., *A Lean Pull System Design Analysed by Value Stream Mapping and Multiple Criteria Decision-Making Method under Demand Uncertainty*. International Journal of Computer Integrated Manufacturing, 2011. 24(3): p. 211-228. ISBN: 0951-192X.

- [259] Huang, M., Wang, D., and Ip, W., *Simulation Study of Conwip for a Cold Rolling Plant*. International Journal of Production Economics, 1998. 54(3): p. 257-266. ISBN: 0925-5273.
- [260] Liberopoulos, G. and Dallery, Y., *Comparative Modelling of Multi-Stage Production-Inventory Control Policies with Lot Sizing*. International Journal of Production Research, 2003. 41(6): p. 1273-1298. ISBN: 0020-7543.
- [261] Zhang, Z., *Analysis and Design of Manufacturing Systems with Multiple-Loop Structures*. 2006, Massachusetts Institute of Technology.
- [262] Robinson, D., *Becoming a Translator: An Introduction to the Theory and Practice of Translation*. 2003: Psychology Press. ISBN: 0415300320.
- [263] Stone, P. and Veloso, M., *Multiagent Systems: A Survey from a Machine Learning Perspective*. Autonomous Robots, 2000. 8(3): p. 345-383.
- [264] Jones, M. T., *Artificial Intelligence: A Systems Approach*. 2009: Jones & Bartlett Publishers, LLC. ISBN: 978-0-7637-7337-3.
- [265] Subramaniam, V., Ramesh, T., Lee, G., Wong, Y., and Hong, G., *Job Shop Scheduling with Dynamic Fuzzy Selection of Dispatching Rules*. The International Journal of Advanced Manufacturing Technology, 2000. 16(10): p. 759-764. ISBN: 0268-3768.
- [266] Gunasekaran, A., Patel, C., and Mcgaughey, R., *A Framework for Supply Chain Performance Measurement*. International Journal of Production Economics, 2004. 87(3): p. 333-347.
- [267] Wiendahl, H. P. and Lutz, S., *Production in Networks*. Cirp Annals-Manufacturing Technology, 2002. 51(2): p. 573-586. ISBN: 0007-8506.
- [268] Millington, I. and Funge, J., *Artificial Intelligence for Games*. 2009, Burlington: Morgan Kaufmann Elsevier. ISBN: 978-0-12-374731-0.
- [269] Munakata, T., *Fundamentals of the New Artificial Intelligence: Neural, Evolutionary, Fuzzy and More*. 2008, London: Springer-Verlag ISBN: 978-1-84628-838-8.
- [270] Engelbrecht, A. P., *Computational Intelligence: An Introduction*. 2nd ed. ed. 2007: John Wiley & Sons Ltd. ISBN: 978-0-470-03561-0.
- [271] Wang, Y., *Abstract Intelligence and Cognitive Robots*. Paladyn, 2010. 1(1): p. 66-72. ISBN: 2080-9778.
- [272] Fogel, D. B., *Evolutionary Computation: Toward a New Philosophy of Machine Intelligence*. vol. 1. 2006: Wiley-IEEE Press. ISBN: 0471669512.
- [273] Negnevitsky, M., *Artificial Intelligence: A Guide to Intelligent Systems*. 2005: Addison-Wesley Longman. ISBN: 0321204662.
- [274] Witten, I. H. and Frank, E., *Data Mining: Practical Machine Learning Tools and Techniques*. 2005: Morgan Kaufmann. ISBN: 0120884070.
- [275] Ramos, C., Augusto, J. C., and Shapiro, D., *Guest Editors' Introduction: Ambient Intelligence—the Next Step for Artificial Intelligence*. IEEE Intelligent Systems, 2008: p. 15-18. ISBN: 1541-1672.
- [276] Anderson, J. R., Michalski, R. S., Carbonell, J. G., and Mitchell, T. M., *Machine Learning: An Artificial Intelligence Approach*. vol. 2. 1986: Morgan Kaufmann. ISBN: 0934613001.
- [277] Poole, D. L. and Mackworth, A. K., *Artificial Intelligence: Foundations of Computational Agents*. 2010: Cambridge Univ Pr. ISBN: 978-0-521-51900-7.
- [278] Weise, T., *Global Optimization Algorithms—Theory and Application*. vol. 2. 2008: Free Software Foundation.
- [279] Barricelli, N. A., *Symbiogenetic Evolution Processes Realized by Artificial Methods*. Methodos, 1957. 9(35-36): p. 143-182.
- [280] Fraser, A. S., *Simulation of Genetic Systems by Automatic Digital Computers Vi. Epistasis*. Australian Journal of Biological Sciences, 1957. 13(2): p. 150-162.
- [281] Sivanandam, S. and Deepa, S., *Introduction to Genetic Algorithms*. 2008, Berlin Heidelberg: Springer-Verlag. ISBN: 978-3-540-73189-4.
- [282] Schönberger, J., *Operational Freight Carrier Planning Basic Concept, Optimzation Models and Advanced Memetic Algorithm*. H.-O. Günther and P. V. Beek (Eds.), Advanced Planning and Scheduling, ed. Burkard, R. E., Fleischmann, B., Inderfurth, K., Möhring, R. H., and Voss, S. 2005, Berlin Heidelberg New York: Springer. ISBN: 3540253181.

- [283] Chan, K. and Tansri, H., *A Study of Genetic Crossover Operations on the Facilities Layout Problem*. Computers & industrial engineering, 1994. 26(3): p. 537-550. ISBN: 0360-8352.
- [284] Cantú-Paz, E., *Migration Policies, Selection Pressure, and Parallel Evolutionary Algorithms*. Journal of heuristics, 2001. 7(4): p. 311-334.
- [285] Sakawa, M., *Genetic Algorithms and Fuzzy Multiobjective Optimization*. vol. 14. 2002: Springer Netherlands. ISBN: 0792374525.
- [286] Jong, K., *An Analysis of the Behavior of a Class of Genetic Adaptive Systems*, in *Dissertation Abstracts International*. 1975, University of Michigan.
- [287] Whitley, D., *A Genetic Algorithm Tutorial*. Statistics and computing, 1994. 4(2): p. 65-85. ISBN: 0960-3174.
- [288] Ong, Y. and Keane, A., *Meta-Lamarckian Learning in Memetic Algorithms*. IEEE Transactions on Evolutionary Computation, 2004. 8(2): p. 99-110.
- [289] Glover, F., *Future Paths for Integer Programming and Links to Artificial Intelligence*. Computers & Operations Research, 1986. 13(5): p. 533-549. ISBN: 0305-0548.
- [290] Gendreau, M. and Potvin, J. Y., *Tabu Search*. Handbook of Metaheuristics, 2010: p. 41-59.
- [291] Zadeh, L., *Outline of a New Approach to the Analysis of Complex Systems and Decision Processes*. IEEE transactions on Systems, Man, and Cybernetics, 1973. 3(1): p. 28-44.
- [292] Zimmermann, H., *Fuzzy Set Theory--and Its Applications*. 2001: Springer Netherlands.
- [293] Zadeh, L. A., *Outline of a New Approach to the Analysis of Complex Systems and Decision Processes*. Systems, Man and Cybernetics, IEEE Transactions on, 1973(1): p. 28-44. ISBN: 0018-9472.
- [294] Mohit Kumar, Kerstin Thurow, Norbert Stoll, and Stoll, R., *Fuzzy Systems*. Ahmad, T. A., Editor. 2010, InTech. p. 216. ISBN: 978-953-7619-92-3.
- [295] Babuška, R., *Fuzzy Systems, Modeling and Identification*. Delft University of Technology, Department of Electrical Engineering Control Laboratory, Mekelweg, 2003. 4.
- [296] Klimke, W., *Uncertainty Modeling Using Fuzzy Arithmetic and Sparse Grids*, in *Institut für Angewandte Analysis und Numerische Simulation*. 2005, University of Stuttgart: Stuttgart.
- [297] Carlsson, C. and Fuller, R., *Fuzzy Reasoning in Decision Making and Optimization*. vol. 82. 2002: Springer Berlin Heidelberg. ISBN: 3790814288.
- [298] Petrovic, S., Fayad, C., Petrovic, D., Burke, E., and Kendall, G., *Fuzzy Job Shop Scheduling with Lot-Sizing*. Annals of Operations Research, 2008. 159(1): p. 275-292.
- [299] Mitaim, S. and Kosko, B., *The Shape of Fuzzy Sets in Adaptive Function Approximation*. Fuzzy Systems, IEEE Transactions on, 2001. 9(4): p. 637-656. ISBN: 1063-6706.
- [300] Peidro, D. and Vasant, P., *Transportation Planning with Modified S-Curve Membership Functions Using an Interactive Fuzzy Multi-Objective Approach*. Applied Soft Computing, 2010. 11(2): p. 2656-2663. DOI: 10.1016/j.asoc.2010.10.014. ISBN: 1568-4946.
- [301] Zadeh, L. A., *The Concept of a Linguistic Variable and Its Application to Approximate Reasoning--I* 1*. Information Sciences, 1975. 8(3): p. 199-249. ISBN: 0020-0255.
- [302] Dong, W. and Wong, F., *Fuzzy Weighted Averages and Implementation of the Extension Principle*. Fuzzy Sets and Systems, 1987. 21(2): p. 183-199.
- [303] Zadeh, L. A., *A Theory of Approximate Reasoning, Machine Intelligence*. Hayes, D. Michie and L. Mikulich (Eds.), 1979. 9: p. 149-194.
- [304] Mamdani, E. H. and Assilian, S., *An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller*. International Journal of Man-Machine Studies, 1975. 7(1): p. 1-13. ISBN: 0020-7373.
- [305] Mohan, B. and Sinha, A., *The Simplest Fuzzy Two-Term Controllers: Mathematical Models and Stability Analysis*. International Journal of Automation and Control, 2008. 2(1): p. 5-21. ISBN: 1740-7516.
- [306] Sugeno, M., *Industrial Applications of Fuzzy Control*. 1985: Elsevier Science Ltd 278 pages. ISBN: 0444878297.
- [307] Liu, X., *Parameterized Defuzzification with Maximum Entropy Weighting Function--Another View of the Weighting Function Expectation Method*. Mathematical and computer modelling, 2007. 45(1-2): p. 177-188. ISBN: 0895-7177.

- [308] Chandramohan, A., Rao, M. V. C., and Arumugam, M. S., *Two New and Useful Defuzzification Methods Based on Root Mean Square Value*. Soft Computing-A Fusion of Foundations, Methodologies and Applications, 2006. 10(11): p. 1047-1059. ISBN: 1432-7643.
- [309] Mcculloch, W. S. and Pitts, W., *A Logical Calculus of the Ideas Immanent in Nervous Activity*. Bulletin of Mathematical Biology, 1943. 5(4): p. 115-133. ISBN: 0092-8240.
- [310] Rosenblatt, F., *The Perceptron: A Probabilistic Model for Information Storage and Organization in the Brain*. Psychological review, 1958. 65(6): p. 386. ISBN: 1939-1471.
- [311] Rosenblatt, F., *Perceptron Simulation Experiments*. Proceedings of the IRE, 1960. 48(3): p. 301-309. ISBN: 0096-8390.
- [312] Kim, J., Lee, S., and Cho, B., *Discrimination of Li-Ion Batteries Based on Hamming Network Using Discharging/Charging Voltage Pattern Recognition for Improved State of Charge Estimation*. Journal of Power Sources, 2011. 196(4): p. 2227-2240 DOI: 10.1016/j.jpowsour.2010.08.119. ISBN: 0378-7753.
- [313] Badel, S., Schmid, A., and Leblebici, Y., *Cmos Realization of Two-Dimensional Mixed Analog-Digital Hamming Distance Discriminator Circuits for Real-Time Imaging Applications*. Microelectronics Journal, 2008. 39(12): p. 1817-1828. ISBN: 0026-2692.
- [314] Hagan, M. T., Demuth, H. B., and Beale, M., *Perceptron Learning Rule*. In Neural Network Design. 1996, PWS-Kent, Boston, MA. ISBN: 0-9717321-0-8.
- [315] Haykin, S., *Feedforward Neural Networks: An Introduction*. In Nonlinear Dynamical Systems: Feedforward Neural Network Perspectives, Sandberg, I. W., Editor. 2001, Wiley-Interscience. ISBN: 0471349119.
- [316] Hagan, M. T., Demuth, H. B., and Beale, M., *Performance Surfaces and Optimum Points*. In Neural Network Design. 1996, PWS-Kent, Boston, MA. ISBN: 0-9717321-0-8.
- [317] Hagan, M. T., Demuth, H. B., and Beale, M., *Performance Optimzation*. In Neural Network Design. 1996, PWS-Kent, Boston, MA. ISBN: 0-9717321-0-8.
- [318] Hush, D. R. and Horne, B. G., *Progress in Supervised Neural Networks*. Signal Processing Magazine, IEEE, 1993. 10(1): p. 8-39. ISBN: 1053-5888.
- [319] Back, A. D., *Radial Basis Functions*. In Handbook of Neural Network Signal Processing, Hu, Y. and Hwang, J., Editors. 2002, CRC Press LLC: New York. p. 2525-2526. ISBN: 0-8493-2359-2.
- [320] Jwo, D. J. and Lai, C. C., *Neural Network-Based Gps Gdop Approximation and Classification*. GPS Solutions, 2007. 11(1): p. 51-60. ISBN: 1080-5370.
- [321] Chang, G. W., Chen, C. I., and Teng, Y. F., *Radial-Basis-Function-Based Neural Network for Harmonic Detection*. Industrial Electronics, IEEE Transactions on, 2010. 57(6): p. 2171-2179. ISBN: 0278-0046.
- [322] Kuo, R., Hu, T. L., and Chen, Z. Y. *Application of Radial Basis Function Neural Network for Sales Forecasting*. In International Asia Conference on Informatics in Control, Automation and Robotics, 2009. CAR '09. 2009. Bangkok IEEEExplore. DOI: 10.1109/CAR.2009.97 ISBN: 978-1-4244-3331-5
- [323] El-Shafie, A., Abdelazim, T., and Noureldin, A., *Neural Network Modeling of Time-Dependent Creep Deformations in Masonry Structures*. Neural Computing & Applications, 2010. 19(4): p. 583-594. ISBN: 0941-0643.
- [324] Looney, C., *Radial Basis Functional Link Nets and Fuzzy Reasoning*. Neurocomputing, 2002. 48(1-4): p. 489-509. ISBN: 0925-2312.
- [325] Corsini, G., Diani, M., Grasso, R., De Martino, M., Mantero, P., and Serpico, S., *Radial Basis Function and Multilayer Perceptron Neural Networks for Sea Water Optically Active Parameter Estimation in Case Ii Waters: A Comparison*. International Journal of Remote Sensing, 2003. 24(20): p. 3917-3932. ISBN: 0143-1161.
- [326] Khajeh, A. and Modarress, H., *Prediction of Solubility of Gases in Polystyrene by Adaptive Neuro-Fuzzy Inference System and Radial Basis Function Neural Network*. Expert Systems with Applications, 2010. 37(4): p. 3070-3074. ISBN: 0957-4174.
- [327] Panda, S., Chakraborty, D., and Pal, S., *Flank Wear Prediction in Drilling Using Back Propagation Neural Network and Radial Basis Function Network*. Applied Soft Computing, 2008. 8(2): p. 858-871. ISBN: 1568-4946.

- [328] De Silva, C. R., Ranganath, S., and De Silva, L. C., *Cloud Basis Function Neural Network: A Modified Rbf Network Architecture for Holistic Facial Expression Recognition*. Pattern Recognition, 2008. 41(4): p. 1241-1253. ISBN: 0031-3203.
- [329] Orr, M., Hallam, J., Takezawa, K., Murray, A., Ninomiya, S., Oide, M., and Leonard, T., *Combining Regression Trees and Radial Basis Function Networks*. International Journal of Neural Systems, 2000. 10(6): p. 453-466. ISBN: 0129-0657.
- [330] Bortman, M. and Aladjem, M., *A Growing and Pruning Method for Radial Basis Function Networks*. Neural Networks, IEEE Transactions on, 2009. 20(6): p. 1039-1045. ISBN: 1045-9227.
- [331] De Jesús Rubio, J., Vázquez, D. M., and Pacheco, J., *Backpropagation to Train an Evolving Radial Basis Function Neural Network*. Evolving Systems, 2010. 1(3): p. 1-8. DOI: 10.1007/s12530-010-9015-9. ISBN: 1868-6478.
- [332] Vakil-Baghmisheh, M. T. and Pavei, N., *Training Rbf Networks with Selective Backpropagation*. Neurocomputing, 2004. 62: p. 39-64. ISBN: 0925-2312.
- [333] Alexandridis, A., Sarimveis, H., and Ninos, K., *A Radial Basis Function Network Training Algorithm Using a Non-Symmetric Partition of the Input Space-Application to a Model Predictive Control Configuration*. Advances in Engineering Software, 2011. 42(10): p. 830-837. DOI: 10.1016/j.advengsoft.2011.05.026. ISBN: 0965-9978.
- [334] Bisschop, J., *Aimms-Optimization Modeling*. 2006: Lulu. Com. ISBN: 1411698991.
- [335] Fahringer, T., Jugravu, A., Pllana, S., Prodan, R., Seragiotto Jr, C., and Truong, H. L., *Askalon: A Tool Set for Cluster and Grid Computing*. Concurrency and Computation: Practice and Experience, 2005. 17(2 4): p. 143-169. ISBN: 1532-0634.
- [336] Zagonel, A. and Corbet, T. F. *Levels of Confidence in System Dynamics Modeling: A Pragmatic Approach to Assessment of Dynamic Models*. In International Conference of the System Dynamics Society. 2006. Nijmegen, Netherlands.
- [337] Liu, D., Tan, K., Huang, S., Goh, C., and Ho, W., *On Solving Multiobjective Bin Packing Problems Using Evolutionary Particle Swarm Optimization*. European Journal of Operational Research, 2008. 190(2): p. 357-382. ISBN: 0377-2217.
- [338] Bradley, S., Hax, A., and Magnanti, T., *Applied Mathematical Programming*. 1977: Addison Wesley. ISBN: 978-0201004649.
- [339] Zhang, X., Huang, G. H., Chan, C. W., Liu, Z., and Lin, Q., *A Fuzzy-Robust Stochastic Multiobjective Programming Approach for Petroleum Waste Management Planning*. Applied Mathematical Modelling, 2010. 34(10): p. 2778-2788. ISBN: 0307-904X.
- [340] Shavandi, H. and Mahlooji, H., *A Fuzzy Queuing Location Model with a Genetic Algorithm for Congested Systems*. Applied Mathematics and Computation, 2006. 181(1): p. 440-456.
- [341] Zimmermann, H. J., *Applications of Fuzzy Set Theory to Mathematical Programming*. Information Sciences, 1985. 36(1-2): p. 29-58. ISBN: 0020-0255.
- [342] Shih, C., Chi, C., and Hsiao, J., *Alternative [Alpha]-Level-Cuts Methods for Optimum Structural Design with Fuzzy Resources*. Computers & structures, 2003. 81(28-29): p. 2579-2587. ISBN: 0045-7949.
- [343] Mitchell, C. and Psihoyios, G., *Modelling Fuzzy Universal Resource Identifiers: A First Approach*. Mathematical and computer modelling, 2005. 42(7-8): p. 867-872. ISBN: 0895-7177.
- [344] Inuiguchi, M. and Ramík, J., *Possibilistic Linear Programming: A Brief Review of Fuzzy Mathematical Programming and a Comparison with Stochastic Programming in Portfolio Selection Problem*. Fuzzy Sets and Systems, 2000. 111(1): p. 3-28. ISBN: 0165-0114.
- [345] Boukezzoula, R., Galichet, S., and Foulloy, L., *Min and Max Operators for Fuzzy Intervals and Their Potential Use in Aggregation Operators*. Fuzzy Systems, IEEE Transactions on, 2007. 15(6): p. 1135-1144. ISBN: 1063-6706.
- [346] Sakawa, M., Nishizaki, I., and Katagiri, H., *Fuzzy Stochastic Multiobjective Programming*. vol. 159. 2011: Springer New York Heidelberg London. DOI: 10.1007/978-1-4419-8402-9. ISBN: 978-1-4419-8401-2.
- [347] Zimmermann, H. J., *Fuzzy Mathematical Programming*. Computers & Operations Research, 1983. 10(4): p. 291-298. ISBN: 0305-0548.

- [348] Zimmermann, H. J., *Fuzzy Programming and Linear Programming with Several Objective Functions* 1*. Fuzzy Sets and Systems, 1978. 1(1): p. 45-55. ISBN: 0165-0114.
- [349] Fayad, C. and Petrovic, S., *A Fuzzy Genetic Algorithm for Real-World Job Shop Scheduling*. Innovations in Applied Artificial Intelligence, 2005. 3533/2005: p. 76-83. DOI: 10.1007/11504894_71.
- [350] Cooper, R., *Introduction to Queueing Theory*. 2nd ed. 1981: Elsevier North Holland, Inc. 347 pages. DOI: 2002/02/27 17:38:31 US/Mountain. ISBN: 978-0444003799.
- [351] Görg, C., *Lecture Notes of Communication Network Ii*. 2010, University Bremen: Bremen.
- [352] Bhat, U. N., *An Introduction to Queueing Theory: Modeling and Analysis in Applications*. 2008: Birkhauser. ISBN: 0817647244.
- [353] Ravindran, A., *Operations Research and Management Science Handbook*. 2008: CRC. ISBN: 0849397219.
- [354] Buzen, J. P., *Computational Algorithms for Closed Queueing Networks with Exponential Servers*. Communications of the ACM, 1973. 16(9): p. 527-531. ISBN: 0001-0782.
- [355] Karlsson, V. V. G., *Multicast Scheduling with Resource Fairness Constraints*. Wireless Netw, 2009. 15: p. 571-583.
- [356] Balsamo, S., *Queueing Networks with Blocking: Analysis, Solution Algorithms and Properties*. Network Performance Engineering, 2011. 5233/2011: p. 233-257. DOI: 10.1007/978-3-642-02742-0_11.
- [357] Reiser, M. and Lavenberg, S. S., *Mean-Value Analysis of Closed Multichain Queuing Networks*. Journal of the ACM (JACM), 1980. 27(2): p. 313-322. ISBN: 0004-5411.
- [358] Saltelli, A., Ratto, M., Andres, T., Campolongo, F., and Al, E., *Global Sensitivity Analysis: The Primer*. 2008: John Wiley & Sons, Ltd. DOI: 10.1002/9780470725184.fmatter. ISBN: 9780470725184.
- [359] Ke, J. C. and Lin, C. H., *Sensitivity Analysis of Machine Repair Problems in Manufacturing Systems with Service Interruptions*. Applied Mathematical Modelling, 2008. 32(10): p. 2087-2105. ISBN: 0307-904X.
- [360] Womack, J. P., Jones, D. T., and Roos, D., *The Machine That Changed the World*. 2007: HarperPaperbacks. 336 pages. ISBN: 978-0060974176.
- [361] Giménez, C. and Ventura, E., *Supply Chain Management as a Competitive Advantage in the Spanish Grocery Sector*. International Journal of Logistics Management, The, 2003. 14(1): p. 77-88. ISBN: 0957-4093.
- [362] Xiaomei, L., Zhaofang, M., Guohong, X., and Fu, J. *Study on Manufacturing Supply Chain Leagile Strategy Driven Factors Based on Customer Value*. In 4th International Conference on Wireless Communications, Networking and Mobile Computing, 2008. WiCOM '08. . 2008: IEEE Xplore. DOI: 10.1109/WiCom.2008.1642 ISBN: 978-1-4244-2107-7
- [363] Cowton, R., *Making Sense of Just-in-Time Production: A Resource-Based Perspective*. Omega, 1994. 22(5): p. 427-441. DOI: 10.1016/0305-0483(94)90025-6. ISBN: 0305-0483.
- [364] Wadhwa, S., Mishra, M., and Saxena, A., *A Network Approach for Modeling and Design of Agile Supply Chains Using a Flexibility Construct*. International journal of flexible manufacturing systems, 2007. 19(4): p. 410-442. DOI: 10.1007/s10696-008-9044-x. ISBN: 0920-6299.
- [365] Laure, W. *Cycle Time and Bottleneck Analysis*. In Advanced Semiconductor Manufacturing Conference and Workshop, 1999 IEEE/SEMI. 1999. Boston, MA , USA IEEE. DOI: 10.1109/ASMC.1999.798179 ISBN: 0780352173.
- [366] Christopher, M., *The Agile Supply Chain:: Competing in Volatile Markets*. Industrial Marketing Management, 2000. 29(1): p. 37-44. ISBN: 0019-8501.
- [367] Vázquez-Bustelo, D., Avella, L., and Fernández, E., *Agility Drivers, Enablers and Outcomes: Empirical Test of an Integrated Agile Manufacturing Model*. International Journal of Operations & Production Management, 2007. 27(12): p. 1303-1332. ISBN: 0144-3577.
- [368] Zhang, Z. and Sharifi, H., *A Methodology for Achieving Agility in Manufacturing Organisations*. International Journal of Operations & Production Management, 2000. 20(4): p. 496-513. ISBN: 0144-3577.

- [369] Scholz-Reiter, B., Wirth, F., Freitag, M., Dashkovskiy, S., Jagalski, T., Beer, C., and Rüffer, B. *Some Remarks on the Stability of Production Networks*. In Operations Research Proceedings 2005. 2006. ISBN: 978-3-540-32539-0.
- [370] Scholz-Reiter, B., Jagalski, T., De Beer, C., and Freitag, M. *Autonomous Shop Floor Control Considering Set-up Times*. In 40th CIRP Int. Seminar on Manufacturing Systems. 2007. Liverpool, UK: Citeseer.
- [371] Vogel, A., Fischer, M., Jaehn, H., and Teich, T., *Real-World Shop Floor Scheduling by Ant Colony Optimization*. In Ant Algorithms, Dorigo, M., Editor. 2002, Springer: Berlin-Heidelberg. p. 173-198.
- [372] Scholz-Reiter, B., Freitag, M., De Beer, C., and Jagalski, T. *Modelling and Analysis of Autonomous Shop Floor Control*. In 38th Annu. CIRP International Seminar on Manufacturing Systems. 2005. Florianopolis, Brazil.
- [373] Scholz-Reiter, B., Rekersbrink, H., and Görges, M., *Dynamic Flexible Flow Shop Problems--Scheduling Heuristics Vs. Autonomous Control*. Cirp Annals-Manufacturing Technology, 2010. 59(1): p. 465-468. ISBN: 0007-8506.
- [374] Nyhuis, P. and Vogel, M., *Adaptation of Logistic Operating Curves to One-Piece Flow Processes*. International Journal of Productivity and Performance Management, 2006. 55(3/4): p. 284-299. ISBN: 1741-0401.
- [375] Lee, H., Padmanabhan, P., and Whang, S., *The Paralyzing Curse of the Bullwhip Effect in a Supply Chain*. 1997, Stanford University: Stanford, CA
- [376] Daley, D., *General Customer Impatience in the Queue $G_i/G/1$* . Journal of Applied Probability, 1965. 2(1): p. 186-205.
- [377] Tay, N. and Linn, S., *Fuzzy Inductive Reasoning, Expectation Formation and the Behavior of Security Prices*. Journal of Economic Dynamics and Control, 2001. 25(3-4): p. 321-361.
- [378] Mehra, A. and Scholz-Reiter, *Toward Learning Autonomous Pallets by Using Fuzzy Rules, Applied in a Conwip System*. Under revision by International Journal of Advanced Manufacturing Systems, Since Feb. 2011.
- [379] Wang, H., *Flexible Flow Shop Scheduling: Optimum, Heuristics and Artificial Intelligence Solutions*. Expert Systems, 2005. 22(2): p. 78-85. ISBN: 1468-0394.
- [380] Haridy, S. and Wu, Z., *Univariate and Multivariate Control Charts for Monitoring Dynamic-Behavior Processes: A Case Study*. Journal of Industrial Engineering and Management, 2009. 2(3): p. 464. ISBN: 2013-0953.
- [381] Mamdani, E., *Application of Fuzzy Algorithms for Control of Simple Dynamic Plant*. Proc. IEE, 1974. 121(12): p. 1585-1588.
- [382] Ying, H., Ding, Y., Li, S., and Shao, S., *Comparison of Necessary Conditions for Typical Takagi-Sugeno and Mamdani Fuzzy Systems as Universal Approximators*. Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, 2002. 29(5): p. 508-514.
- [383] Pfluger, N., Yen, J., and Langari, R. *A Defuzzification Strategy for a Fuzzy Logic Controller Employing Prohibitive Information in Command Formulation*. In IEEE International Conference on Fuzzy Systems, 1992. 2002. San Diego, CA , USA IEEE. DOI: 10.1109/FUZZY.1992.258746 ISBN: 0780302362.
- [384] Gurgur, C. and Altiok, T., *Approximate Analysis of Decentralized, Multi-Stage, Pull-Type Production/Inventory Systems*. Annals of Operations Research, 2004. 125(1): p. 95-116. ISBN: 0254-5330.
- [385] Gurgur, C. and Altiok, T., *Analysis of Decentralized Multi-Product Pull Systems with Lost Sales*. Naval Research Logistics, 2007. 54(4): p. 357-370.
- [386] Balbo, G., Bruell, S., and Sereno, M., *On the Relations between Bcnp Queueing Networks and Product Form Solution Stochastic Petri Nets*, in 10th International Workshop on Petri Nets and Performance Models (PNPM '03). 2003, IEEE: Urbana, Illinois DOI: <http://doi.ieeecomputersociety.org/10.1109/PNPM.2003.1231547>. ISBN: 0-7695-1976-8.
- [387] Baskett, F., Chandy, K., Muntz, R., and Palacios, F., *Open, Closed, and Mixed Networks of Queues with Different Classes of Customers*. Journal of the ACM (JACM), 1975. 22(2): p. 248-260. ISBN: 0004-5411.

- [388] Akyildiz, I., *Mean Value Analysis of Closed Queueing Networks with Erlang Service Time Distributions*. Computing, 1987. 39(3): p. 219-232. ISBN: 0010-485X.
- [389] Hoyme, K., Bruell, S., Afshari, P., and Kain, R., *A Tree-Structured Mean Value Analysis Algorithm*. ACM Transactions on Computer Systems (TOCS), 1986. 4(2): p. 178-185. ISBN: 0734-2071.
- [390] Jain, M., Maheshwari, S., and Baghel, K., *Queueing Network Modelling of Flexible Manufacturing System Using Mean Value Analysis*. Applied Mathematical Modelling, 2008. 32(5): p. 700-711. ISBN: 0307-904X.
- [391] Mehraei, A., Karimi, H. R., Rügge, I., and Scholz-Reiter, B. *Application of Learning Pallets for Real-Time Scheduling by Use of Artificial Neural Network* In SKIMA2011, 5th IEEE International Conference on Software, Knowledge, Information Management and Applications. 2011. University of Sannio, Benevento, Italy: To be published by IEEE Xplore.
- [392] Mehraei, A. and Scholz-Reiter, B. *Towards Learning Pallets Applied in Pull Control Job-Open Shop Problem*. In International Symposium on Assembly and Manufacturing (ISAM), 2011 IEEE. 2011. DOI: 10.1109/ISAM.2011.5942354 ISBN: 978-1-61284-342-1
- [393] Polastre, J., Szewczyk, R., and Culler, D. *Telos: Enabling Ultra-Low Power Wireless Research*. In IPSN '05 Proceedings of the 4th international symposium on Information processing in sensor networks 2005. Piscataway, NJ, USA: IEEE Press. ISBN: 0780392027.
- [394] Son, V. Q., Wenning, B. L., Gorg, C., and Timm-Giel, A. *Wisecomsys: A Tool for Data Collection and Management of Wireless Sensor Networks*. In International Conference on Advanced Technologies for Communications (ATC), 2010 2010. Ho Chi Minh City IEEE Xplore. DOI: 10.1109/ATC.2010.5672724 ISBN: 978-1-4244-8875-9
- [395] Müller, H., Pezzè, M., and Shaw, M. *Visibility of Control in Adaptive Systems*. In Second International Workshop on Ultra-Large-Scale Software-Intensive Systems (ULSSIS 2008), at the International Conference on Software Engineering (ICSE 2008). 2008. Leipzig, Germany: Association for Computing Machinery, One Astor Plaza 1515 Broadway, 17 th Floor New York NY 10036-5701 USA. ISBN: 0270-5257.
- [396] Skittner, L., *General Systems Theory: Problems, Perspectives, Practice*. 2nd Edition ed. 2005, Singapore: World Scientific Pub Co Inc. ISBN: 981256389X.
- [397] Franzen, G. and Moriarty, S., *The Science and Art of Branding*. 2008: ME Sharpe. ISBN: 978-0-7656-1791-0.
- [398] Groff, T. R. and Jones, T. P., *Introduction to Knowledge Management: Km in Business*. First ed. 2003: Butterworth-Heinemann. 183. ISBN: 0750677287.
- [399] Wenfang, S. and Huaizhen, Y. *Research on Entropy Model of Order Degree of Fractal Supply Chain Network*. In 2008 International Symposium on Electronic Commerce and Security. 2008. Los Alamitos, CA, USA. DOI: <http://doi.ieeecomputersociety.org/10.1109/ISECS.2008.74>. ISBN: 978-0-7695-3258-5.
- [400] Comte, A. and Jou, D., *Non-Equilibrium Thermodynamics and Anomalous Diffusion*. Journal of Physics A: Mathematical and General, 1996. 29: p. 4321.
- [401] Meralo, Y. and Petter, A., *The Sage Handbook of Complexity and Management*. Allen, P., Maguire, S., and Mckelvey, B., Editors. 2011, Sage Publications Ltd: London, California. ISBN: 978-1-84787-569-3.
- [402] *Modelling Driver Behaviour in Automotive Environments: Critical Issues in Driver Interactions with Intelligent Transport Systems*. Cacciabue, P. C., Editor. 2007, Springer-Verlag New York Inc. ISBN: 1846286174.
- [403] Wang, A., Afshar, P., and Wang, H., *Complex Stochastic Systems Modelling and Control Via Iterative Machine Learning*. Neurocomputing, 2008. 71(13-15): p. 2685-2692. ISBN: 0925-2312.
- [404] Wang, C., Liu, T., and Wang, C. H. *Deterministic Learning and Pattern-Based Nn Control*. In International Symposium on Intelligent Control, 2007. ISIC 2007. IEEE 22nd 2007. Singapore: IEEE Xplore. DOI: 10.1109/ISIC.2007.4450875 ISBN: 1085-1992.
- [405] Chien, C. J., *A Combined Adaptive Law for Fuzzy Iterative Learning Control of Nonlinear Systems with Varying Control Tasks*. Fuzzy Systems, IEEE Transactions on, 2008. 16(1): p. 40-51. ISBN: 1063-6706.

- [406] Huang, S., Tan, K., and Lee, T., *Neural Network Learning Algorithm for a Class of Interconnected Nonlinear Systems*. Neurocomputing, 2009. 72(4-6): p. 1071-1077. ISBN: 0925-2312.
- [407] Seger, C. A. and Miller, E. K., *Category Learning in the Brain*. Annual review of neuroscience, 2011. 33: p. 203-219. ISBN: 0147-006X.
- [408] Ebert, T., Bänfer, O., and Nelles, O., *Multilayer Perceptron Network with Modified Sigmoid Activation Functions*. Artificial Intelligence and Computational Intelligence, 2010. 6319/2010: p. 414-421. DOI: 10.1007/978-3-642-16530-6_49.
- [409] Lehtokangas, M., Saarinen, J., Kaski, K., and Huuhtanen, P., *Initializing Weights of a Multilayer Perceptron Network by Using the Orthogonal Least Squares Algorithm*. Neural Computation, 1995. 7(5): p. 982-999. ISBN: 0899-7667.
- [410] Hebb, D. O., *The Organisation of Behaviour*. 1949, Wiley: New York.
- [411] Widrow, B. and Lehr, M. A. *30 Years of Adaptive Neural Networks: Perceptron, Madaline, and Backpropagation*. In Proceedings of the IEEE. 1990. Stanford Univ., CA IEEE Xplore. DOI: 10.1109/5.58323 ISBN: 0018-9219.
- [412] Giambene, G., *Queueing Theory and Telecommunications: Networks and Applications*. 2005: Springer-Verlag New York Inc. ISBN: 0387240659.
- [413] Kesavadas, T. and Sudhir, A. *Computational Steering in Simulation of Manufacturing Systems*. In IEEE International Conference on Robotics and Automation, 2000. Proceedings. ICRA'00. 2000. San Francisco, CA , USA IEEE Explore. DOI: 10.1109/ROBOT.2000.846428 ISBN: 0780358864.
- [414] Bocharov, P. P. and D'apice, C., *Queueing Theory*. 2004: Ridderprint bv, Ridderkerk. ISBN: 906764398X.
- [415] Cooper, R. B., *Introduction to Queueing Theory*. 2nd Edition ed. 1981, New York: Elsevier North Holland, Inc. DOI: 2002/02/27 17:38:31 US/Mountain. ISBN: 978-0444003799.
- [416] Dombacher, C., *Stationary Queueing Models with Aspects of Customer Impatience and Retrial Behaviour*. 2009, Telecom. p. 131.
- [417] Willig, A., *A Short Introduction to Queueing Theory*. 1999, Technical University Berlin, Telecommunication Networks Group.
- [418] Mitrani, I., *Simulation Techniques for Discrete Event Systems*. vol. 14. 1982, Cambridge NewYork Melbourne: Cambridge Univ Press. ISBN: 0521282829.

Appendix A

1. QLE-simple estimation (without Fuzzy), with supply rate following the Neg-Exp $\beta = 55\text{min}$.

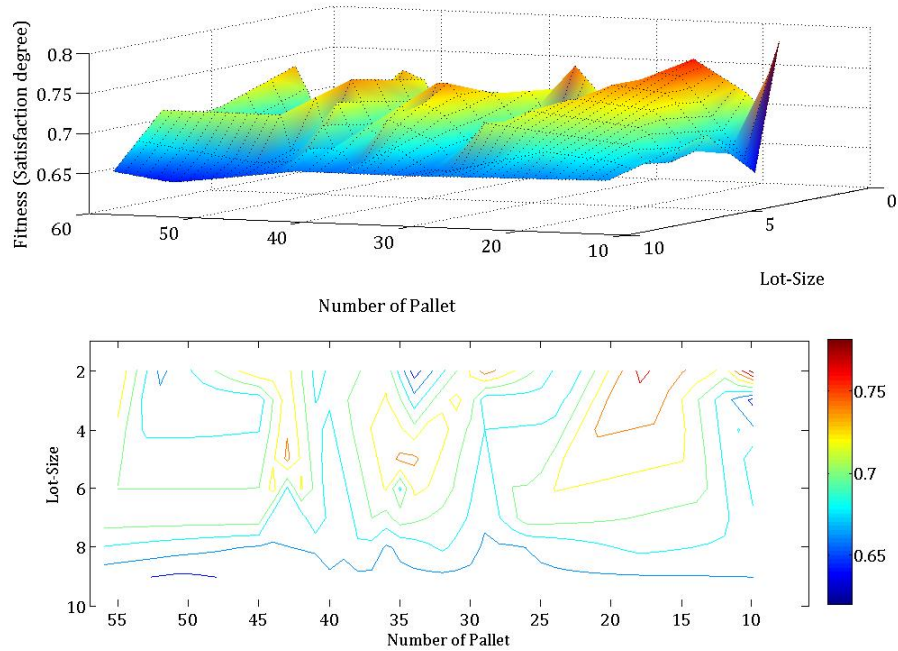


Figure 104: QLE without Fuzzy Supply Neg-Exp 55 min.

2. QLE with Fuzzy estimation, with supply rate following the Neg-Exp $\beta = 55\text{min}$.

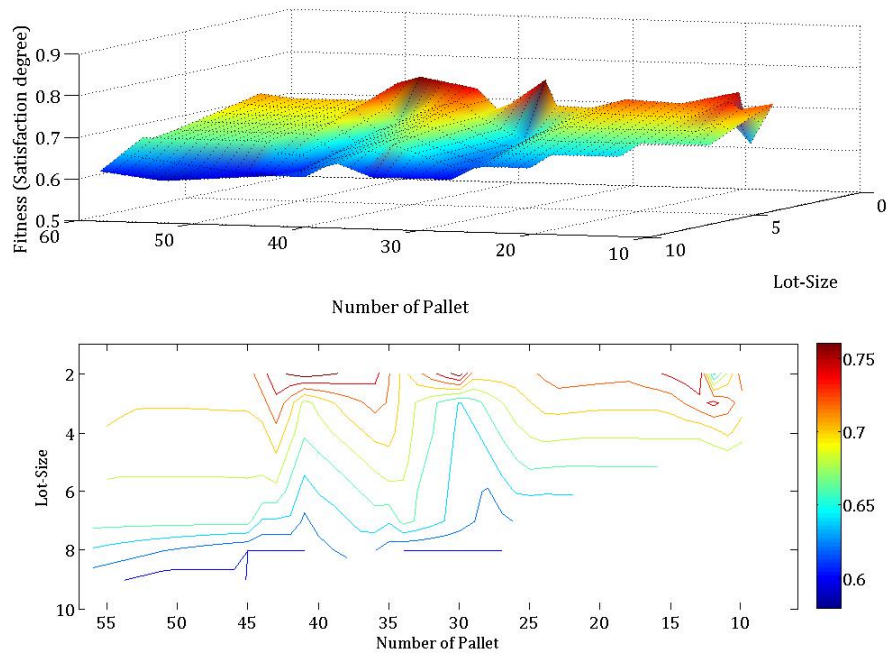


Figure 105: QLE with Fuzzy, Supply Neg-Exp 55 min.

3. QLE-simple, with flexible lot-size, and with supply rate following the Neg-Exp $\beta = 55\text{min}$.

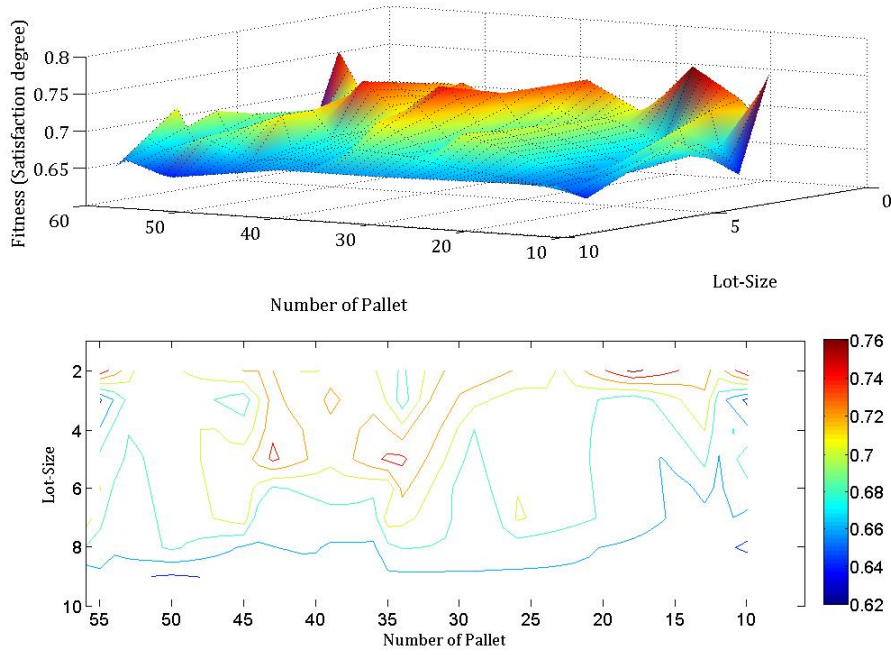


Figure 106: QLE-Simple with flexible lot-size, Supply Neg-Exp 55 min.

4. QLE-Fuzzy with use of flexible lot-size for pallets, with supply rate following the Neg-Exp $\beta = 55\text{min}$.

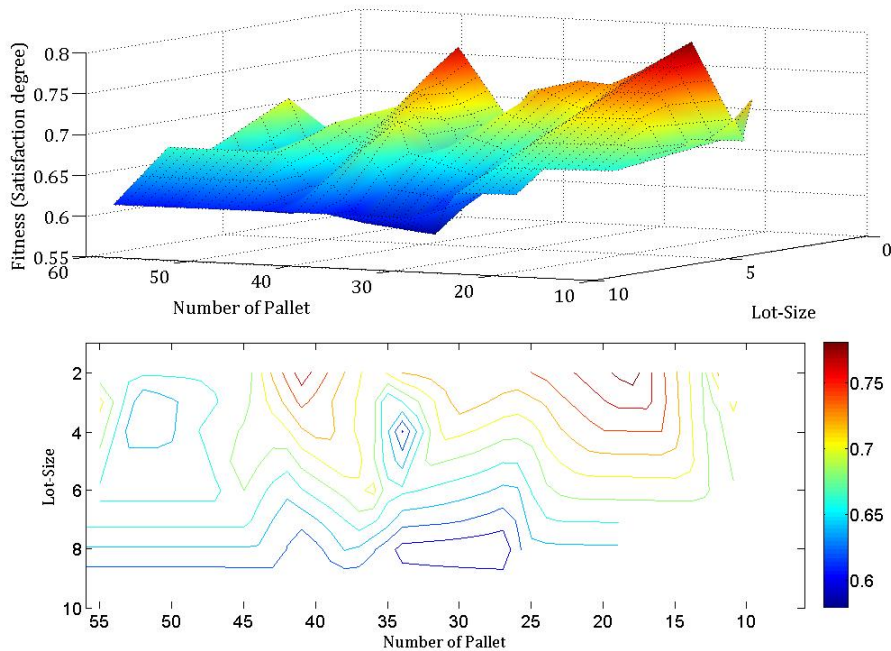


Figure 107: QLE-Fuzzy with flexible lot-size, Supply Neg-Exp 55 min.

5. Conventional (following the least predefined lines with least processing time for each type), with supply rate following the Neg-Exp $\beta = 55\text{min}$.

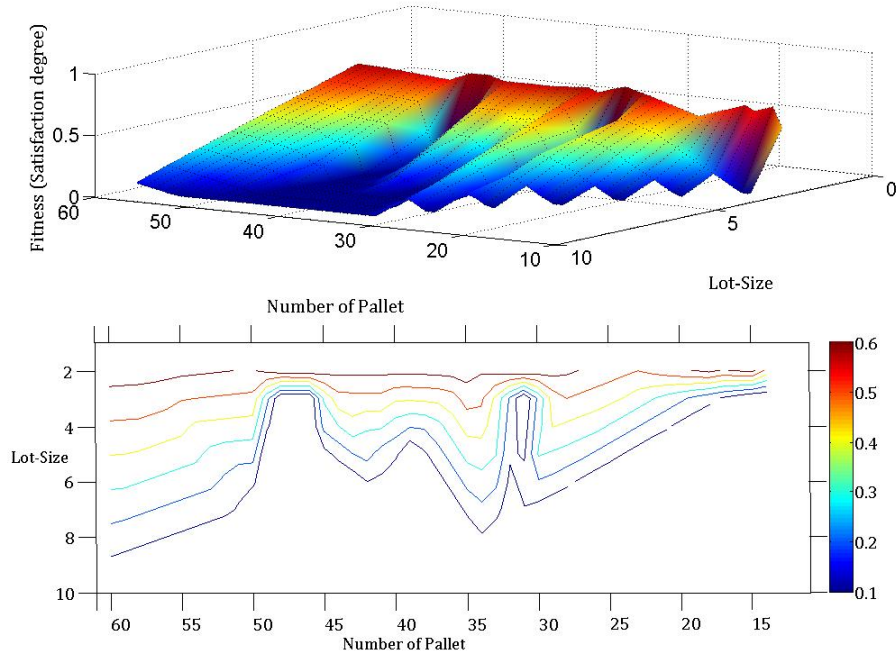


Figure 108: Conventional, Supply Neg-Exp 55 min.

6. Fuzzy Lpallet, with supply rate following the Neg-Exp $\beta = 55$ min.

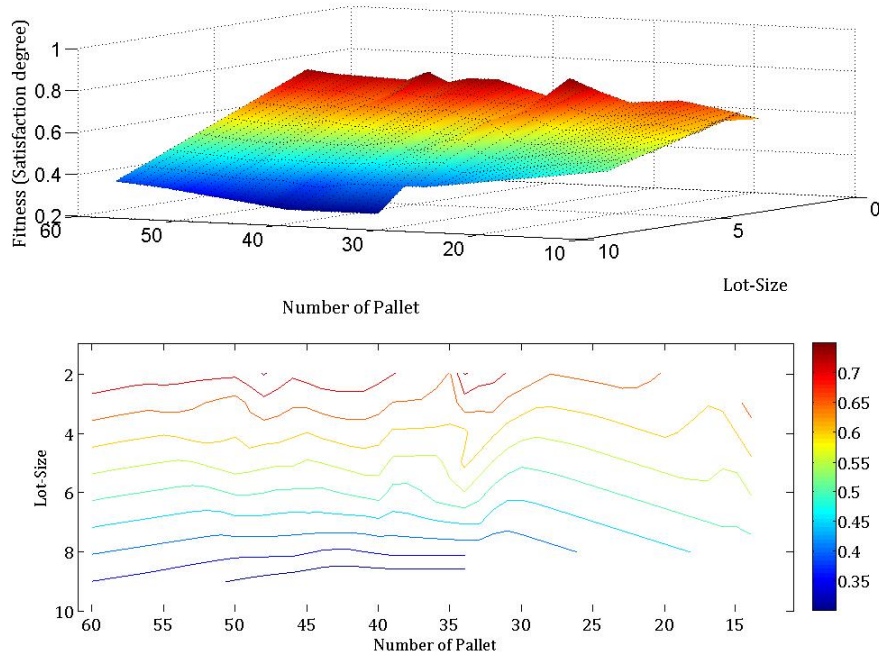


Figure 109: Fuzzy Lpallet, Supply Neg-Exp 55 min.

7. When supply rate follows neg-exponential distribution ($\beta = 55$ min), then the entrance inter-arrival time for replenishment of semi-finished products to OEM follows neg-exponential distribution. Its pdf is approximated by neg-exp with $\lambda = \frac{1}{\beta} = 0.37$. Moreover, the neg-exponential distribution is described by the pdf $f(x) = \frac{1}{\beta} \exp\left(-\frac{x}{\beta}\right)$.

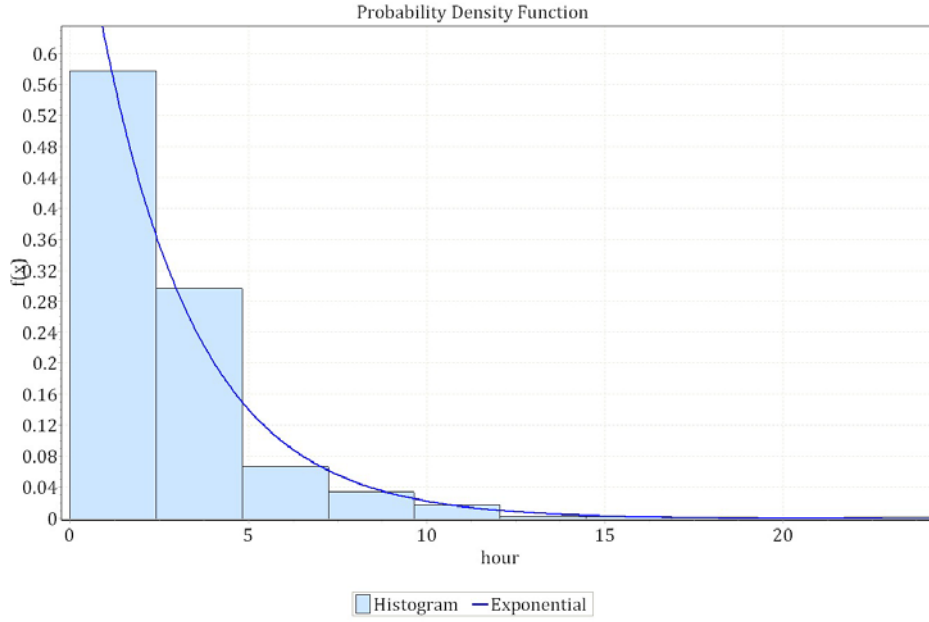


Figure 110: The pdf of the entrance inter-arrival time for replenishment of semi-finished products to OEM that follows neg-exp distribution.

8. The supply rate of sources follow the normal distribution with pdf $f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$, where $N(\mu = 55min, \sigma = 5)$. Then the entrance inter-arrival time for replenishment of semi-finished products to OEM is best approximated by general logistic distribution (pdf) as with $k = 0.18, \sigma = 1.22, \mu = 2.41$.

$$f(x) = \begin{cases} \frac{1}{1 + \left(1 + k \left(\frac{x-\mu}{\sigma}\right)\right)^{-1/k}} & k \neq 0 \\ \frac{\exp\left(-\left(\frac{x-\mu}{\sigma}\right)\right)}{\sigma \left[1 + \exp\left(-\left(\frac{x-\mu}{\sigma}\right)\right)\right]^2} & k = 0 \end{cases} \quad (4.1.3)$$

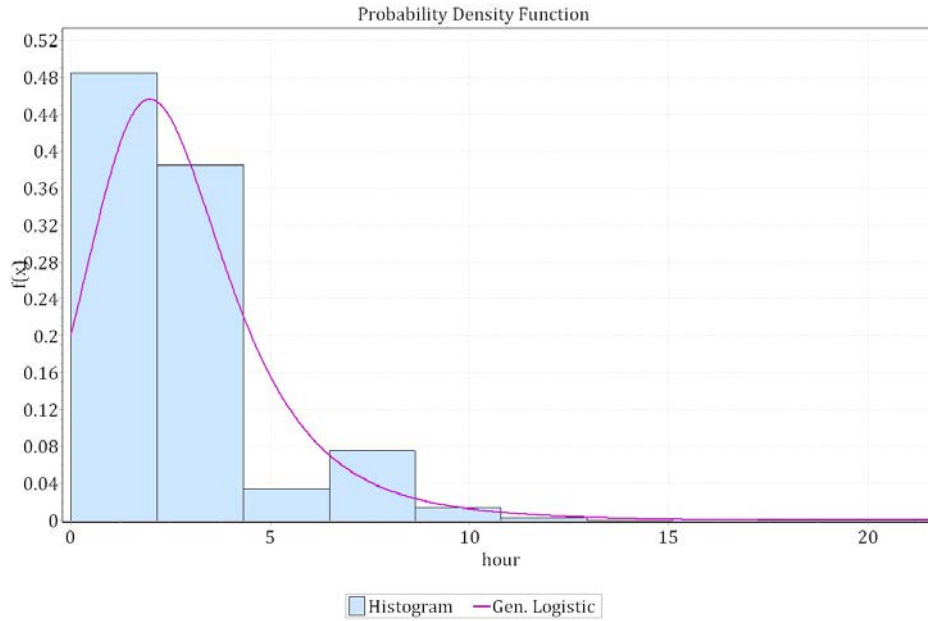


Figure 111: The pdf of the entrance inter-arrival time for replenishment of semi-finished products to OEM.

9. QLE with simple estimation, and with supply rate following the normal distribution with $N(\mu = 55min, \sigma = 5)$.

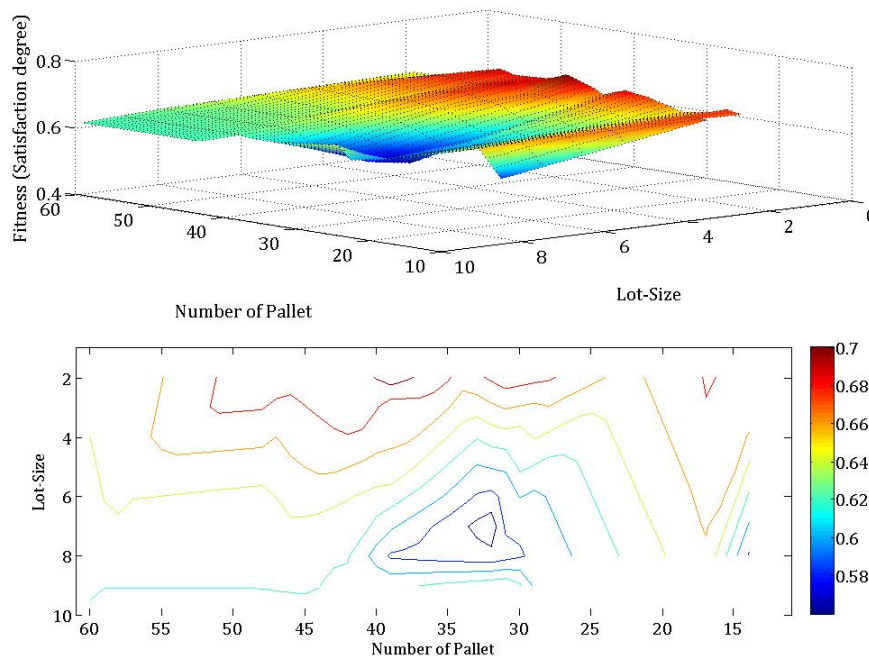


Figure 112: QLE, supply rate follow normal distribution with $\mu=55min$ and $\sigma=5$.

10. QLE with fuzzy estimation, and with supply rate following the normal distribution with $N(\mu = 55min, \sigma = 5)$.

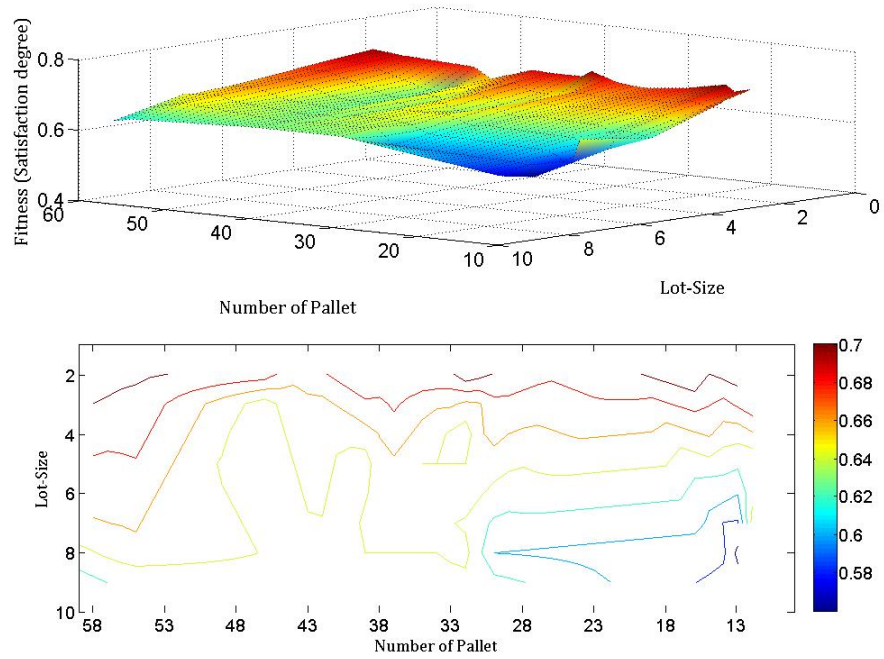


Figure 113: QLE with fuzzy, supply rate follow normal distribution with $\mu=55min$ and $\sigma=5$.

11. Using Fuzzy Lpallet, with a supply rate which follows the normal distribution with $N(\mu = 55min, \sigma = 5)$.

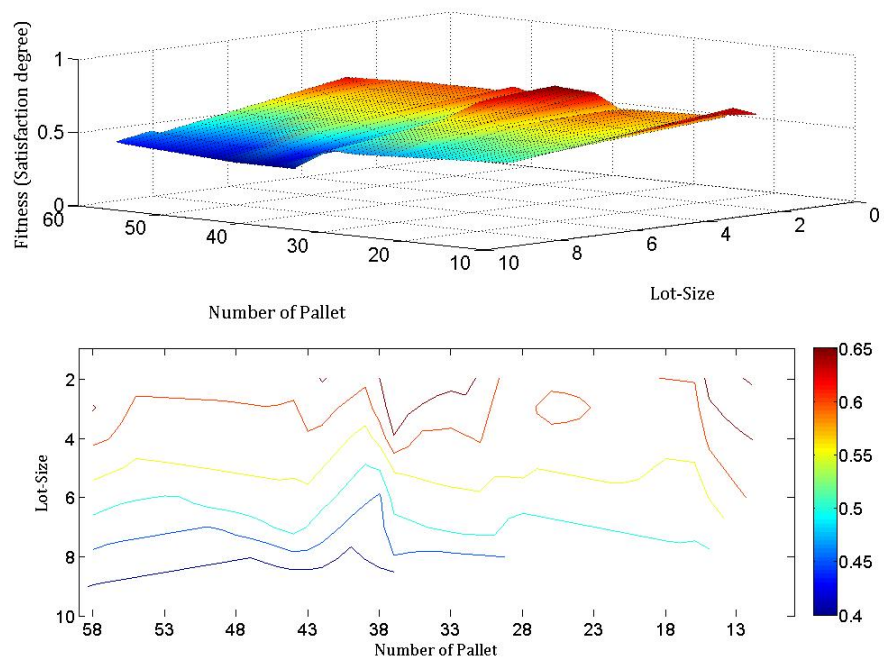


Figure 114: Fuzzy Lpallet, supply rate follow normal distribution with $\mu=55min$ and $\sigma=5$.

Appendix B

When the sources fulfill materials by a rate following neg-exponential inflow ($\beta = \frac{1}{\lambda} = 0.33$) then the pdf of supply for a single type of product at the entrance of OEM follows neg-exp distribution.

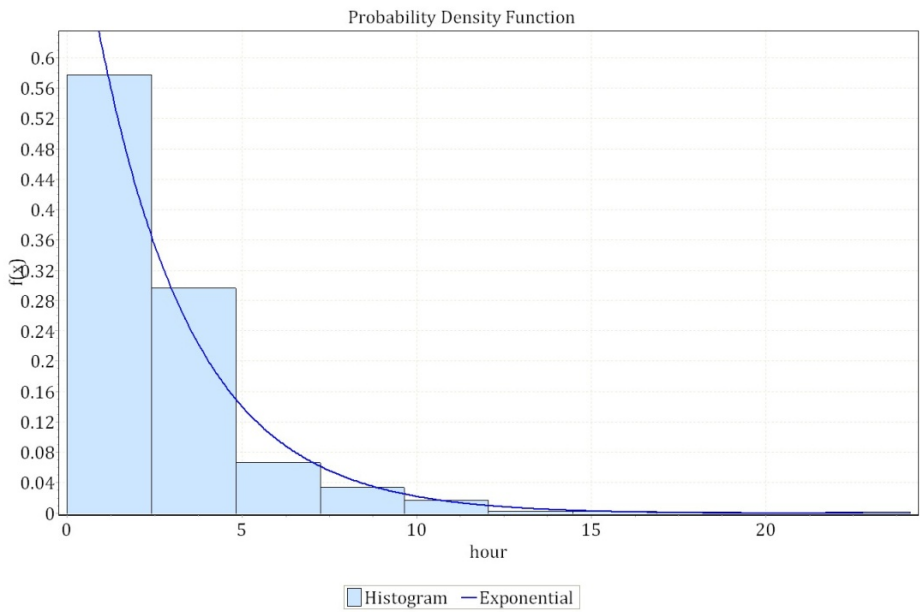


Figure 115: The pdf of one type product at OEM that follows neg-exp distribution.

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und Organisation

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Unternehmensführung
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Planung und Steuerung
produktionstechnischer Systeme

The current dynamic circumstances in supply networks and production environments cause several challenges for industries. To manage these dynamics, a new paradigm of autonomy for processes and objects is underlined by scholars. This paradigm is perceived from two aspects: autonomous logistic processes and autonomous logistic objects. Therefore, this research is divided into conceptual and empirical parts. The part of autonomous logistic processes deals with planning and scheduling tasks, while under the autonomous processes the autonomous objects are supposed to deal with real-time control of material flow. The discrete event simulation approach is employed to explore several methodologies which can bring the notion of intelligent decisions to autonomous objects in logistics. Evolutionary algorithms like genetic algorithm as well as fuzzy logic and artificial neural networks are experimented here. Besides, queuing theory is exploited to analyze assembly networks in production logistics.

ISBN 978-3-95545-056-4

