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Deciding the level of automation for the design of assembly manufacturing systems

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Anas Salmi. Deciding the level of automation for the design of assembly manufacturing systems. Automatic. 2013. dumas-01376652

HAL Id: dumas-01376652

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**Grenoble Institute of Technology – Industrial Engineering School
Grenoble Institute of Innovation**

**Master thesis in Management, Innovation, Technology
Specialty Industrial Engineering
2012/2013**

**Deciding the Level of Automation
for the Design of Assembly Manufacturing Systems**

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June 2013

Acknowledgements

This research is established in the context of Industrial Engineering master thesis graduation at Grenoble Institute of Technology (Grenoble INP) – Industrial Engineering school (GI) and the G-SCOP laboratory.

I would like to take this opportunity to gratefully thank my supervisors

Dr Eric Blanco, Dr Pierre David, and Pr Joshua Summers

for their advices, support, help, feedbacks, and availability. Their participation was very constructive in this work.

I wish to express my gratitude to the Engineering School master members for the valuable education that I learned from them, and the G-SCOP laboratory members for the acceptance, for the resources availability, and for the studies financing.

Résumé

Le contexte industriel s'avère de plus en plus difficile dans le cadre de la mondialisation, de la compétition internationale ou de la complexification des exigences des clients en matière de qualité et de personnalisation de produits. Par conséquent, les industriels ont à optimiser les coûts, leurs ressources et notamment les investissements. L'industrie de l'assemblage n'échappe pas à la règle, et l'optimisation des systèmes et processus d'assemblage forme une réelle problématique de recherche. Ce travail a pour objectif la détermination d'une méthode d'aide à la décision pour la détermination du niveau d'automatisation optimal pour un processus d'assemblage. Cette méthode prendra en compte les caractéristiques du produit, les exigences en matière de qualité, l'aspect ergonomique, l'aspect social, et le contexte économique et financier de l'industriel. La méthode d'aide à la décision a pour objectif la détermination d'un outil pour supporter les designers, décideurs, et managers pour la conception de leurs systèmes d'assemblage de produits.

Une revue de littérature a été élaborée sur ce sujet. Elle a confirmé que la littérature en matière de décision d'automatisation n'est pas abondante, et que la décision à propos de l'automatisation manque de méthodologies assurant notamment la traçabilité des décisions. L'état de l'art de ce rapport a donc balayé les tendances et les axes de recherche en matière d'automatismes dans l'assemblage, le concept du niveau d'automatisation, et les méthodologies existantes en décision à propos de l'automatisation en particulier pour les systèmes d'assemblage.

A la suite de l'analyse de la littérature, les facteurs et paramètres intervenants dans la décision ont été identifiés. Une méthodologie de décision à propos de l'automatisation dédiée aux systèmes d'assemblages a été élaborée et un organigramme de décision a été présenté faisant intervenir les caractéristiques du produit, la séquence d'assemblage, les exigences qualité, l'aspect ergonomique, la stratégie de l'entreprise, le contexte économique et la capacité d'investir de l'industriel, l'aspect social de l'entreprise, l'aspect réglementaire suivant la localisation du manufacturier, ainsi que les informations d'industrialisation pouvant être disponibles assez tôt avant l'étape de conception des systèmes d'assemblages tel que le volume de production, le cycle de vie du produit, le temps de cycle, le taux horaire suivant la localisation planifiée de l'entreprise.

La méthodologie de décision établie nécessite en particulier une méthode graphique standard de représentation et d'ordonnement des séquences d'assemblage. Les méthodes graphiques de représentation de processus d'assemblage ont été analysées, et d'autres méthodes plus globales pouvant être utilisées dans ce domaine ont ensuite été revues. Il a été nécessaire de définir une nouvelle méthode graphique s'inspirant de certaines méthodes rencontrées en les combinant avec et de nouvelles

idées et améliorations liées à notre cas d'application. Après définition de cette méthode nommée *ASML* pour « *Assembly Sequences Modeling Language* », un vocabulaire standardisé d'actions d'assemblage standard a été associé à la méthode faisant de cette méthode une méthode standard dédiée à la représentation des séquences d'assemblages, et permettant de définir, d'organiser, et de représenter ces séquences tout en déduisant les ressources nécessaires et en représentant les contraintes de précédences et de gestion du parallélisme pour des tâches ordinaires ou des tâches à contraintes de précédences. Un exemple d'application a été élaboré pour la représentation d'un exemple d'assemblage en utilisant la méthode *ASML* établie.

Dans le cadre de la décision à propos de l'automatisation, la sélection des tâches à automatiser est faite en se basant sur la méthode graphique *ASML* et l'optimisation de coût d'assemblage. Il est alors nécessaire d'estimer les temps d'assemblage pour des opérations manuelles, automatiques, et robotiques. Pour ce faire, les actions d'assemblage standardisées ont été estimées du point de vue du temps nécessaire pour les trois technologies en faisant intervenir les paramètres impactant le temps pour chacun des actions et pour chacune des technologies. Là encore, ce travail s'est appuyé sur les multiples expériences relevées dans la littérature.

Le travail a été conclu par une validation de la méthode et des timings par une reprise de l'exemple d'application d'assemblage et l'estimation de la séquence obtenue pour un assemblage manuel, automatique, robotique, et deux combinaisons hybrides. Les interprétations donnent des éléments tangibles en ce qui concerne l'optimisation du niveau d'optimisation. De multiples ouvertures et perspectives à ce travail en matière d'outils d'aide à la décision et d'analyse du niveau d'automatisation optimal pour les lignes d'assemblages ont ainsi été dégagées.

ABSTRACT

The design of manufacturing systems with the most suitable Level of Automation (*LoA*) within assembly factories continues to be debated. In fact, manufacturers recognize the importance and delicacy of the decision about automation and that to be competitive it is absolutely necessary for manufacturers to align their products and production with customer demands [1]. This becomes more and more difficult with rapidly changing technologies and shortening product life cycles [37]. In this difficult market context, production systems and supply chains must be designed to handle on one hand such high variety while at the same time achieve mass production quality and productivity [2].

The aim of this master thesis is to define, after a deep literature review about the *LoA* concept and the decision about automation in the literature, a methodology consisting on a support tool for the decision about automation helping processes deciders and designers in dimensioning and designing assembly systems. In fact, it was deduced after the literature review that the research topic is worth doing because it can be confirmed that the support for automation decisions is poor [15] and the discussions on the question to automate or not, are not well documented and the path that lead to the final decision is not traceable [5].

Consequently, the purpose is to define a decision methodology leading to an assembly system *LoA* the most suitable to the manufacturer itself considering its strategic orientations, its context, location, and economic, financial, and social situation. The methodology considers in the decision the product to assemble characteristics and industrialization and production planned information that may be known at an early stage before the assembly system design such as required volume and product market life are exploited in order to optimize the manufacturing cost.

In order to achieve these objectives, an assembly graphical modeling language labeled *ASML* was built and defined for assembly sequences representation allowing a simple, clear, and intuitive representation of assembly and leading to assembly sequencing, planning and optimization. The decision making about automation outline was developed and standards timings and tools that will represent the basis of the decision making were built and defined during the master thesis.

Contents

Résumé.....	II
ABSTRACT	IV
Contents	V
List of Figures.....	VIII
List of Tables.....	IX
CHAPTER 1. INTRODUCTION.....	1
1.1. Industry and automation context.....	1
1.2. Deciding about automation.....	2
1.3. General objectives and purpose of this master thesis	2
CHAPTER 2. Review, Analysis, and Limitations of the existent in Assembly Manufacturing and Automation	4
2.1. Introduction.....	4
2.2. Tendencies and major research orientations in assembly automation.....	4
2.3. The Level of Automation concept	8
2.3.1. The Level of Automation in the literature.....	8
2.3.2. Limitations of the Level of Automation definitions in the literature	10
2.3.3. Building a new definition of the Level of Automation	11
2.4. Deciding about automation in the literature	12
2.4.1. Concepts and Ideas about the decision in the literature	12
2.4.1.1. Concepts and Ideas about using (full) Manual or (full) Automated.....	12
2.4.1.2. Hybrid systems: a mix of Manual and Automated systems	12
2.4.2. Guidelines and frameworks about the decision in the literature	14
2.4.2.1. Guidelines and frameworks for conceiving optimal processes.....	14
2.4.2.2. Guidelines and frameworks for optimizing existent processes	18
2.5. Conclusion	21
CHAPTER 3. The position of the decision in the Manufacturing procedure, Information involved, and the decision basis, tools needed, and outline	22
3.1. Introduction.....	22
3.2. The position of the decision in the Assembly Manufacturing procedure	22
3.2.1. Position with regard to product design.....	22
3.2.1.1. The Design for Assembly approach	23
3.2.1.2. The Methods Time Measurements approach.....	25

3.2.2. Position with regard to Assembly Sequence	25
3.2.3. Position with regard to Quality level required	25
3.2.4. Position with regard to Ergonomics	25
3.2.5. Position with regard to Manufacturer Strategy	25
3.2.6. Position with regard to manufacturer economic situation and ability	26
3.2.7. Position with regard to social aspect	26
3.2.8. Position with regard to Local laws.....	26
3.3. Industrialization Information involved in the decision	26
3.4. The decision making methodology and the solution justification	26
3.5. Outline building for the decision about automation methodology	27
3.6. Conclusion	27
CHAPTER 4. A new modeling language building for assembly sequences representation and optimization: The Assembly Sequences Modeling Language (ASML).....	28
4.1. Introduction.....	28
4.2. The assembly modeling language’s requirements.....	28
4.3. The existent modeling languages useful in assembly sequences representation	29
4.3.1. A literature review about existent modeling languages	29
4.3.2. Discussion about the compatibility of the presented modeling languages and the defined requirements.....	32
4.4. The modeling language definition and building.....	33
4.4.1. The modeling language’s definition and basis	33
4.4.2. The modeling language’s basic structure and symbols.....	33
4.4.3. The modeling language’s assembly motions and vocabulary standardization.....	38
4.5. Example of application	41
4.6. Conclusion	43
CHAPTER 5. Assembly sequence and motions time estimation, analysis, and time involvement in the decision about automation	44
5.1. Introduction.....	44
5.2. Time estimation based on a sequencing using the ASML.....	44
5.3. Time estimation of assembly standardized motion	47
5.3.1. Time estimation for Manual Assembly	47
5.3.2. Time estimation for Automatic Assembly	47
5.3.3. Time estimation for Robotic Assembly	47
5.4. Time savings: a criteria for assembly tasks automating.....	48
5.5. Example of application	48
5.5.1. Estimation in full Manual Assembly	48
5.5.2. Estimation in full Automatic Assembly.....	49
5.5.3. Estimation in full Robotic Assembly	49

5.5.4. Estimation in Hybrid assembly	49
5.5.4.1. Hybrid Manual-Automatic assembly.....	49
5.5.4.2. Hybrid Manual-Automatic-Robotic assembly	51
5.5.5. Interpretations	51
5.6. Conclusion	51
CHAPTER 6. Conclusion and Outlooks	52
References	54
Table of Appendices	61
<i>Appendix 1: Time Standards building</i>	63
<i>Appendix 2: Assembly Automation in the literature</i>	73
<i>Appendix 3: Level of Automation in the literature</i>	76
<i>Appendix 4: Decision about automation in the literature</i>	79
<i>Appendix 5: Literature Graphical representation methods usable for assembly</i>	89
<i>Appendix 6: Time standards in the Literature</i>	95

List of Figures

<i>Figure 1: LoA definitions and taxonomies in the literature</i>	8
<i>Figure 2: Using Manual or Automated</i>	13
<i>Figure 3: Position of the decision about automation with regard to product design</i>	22
<i>Figure 4: The over the wall design [102]</i>	22
<i>Figure 5: Applying DFA for a same product case [102]</i>	23
<i>Figure 6: The Decision about Automation Methodology outline</i>	27
<i>Figure 7: Steps and transitions symbols</i>	33
<i>Figure 8: The initial step symbol</i>	33
<i>Figure 9: Actions within Steps</i>	33
<i>Figure 10: Conditions within transitions</i>	33
<i>Figure 11: Forbidden directly consecutive steps</i>	33
<i>Figure 12: Forbidden directly consecutive steps</i>	34
<i>Figure 13: Multiple starting points in the graphic modeling language</i>	34
<i>Figure 14: AND/OR divergence and convergence symbols</i>	34
<i>Figure 15: The end of assembly symbol consisting on the final product assembly accomplishment</i>	35
<i>Figure 16: A complete assembly product sequencing representation using the modeling language</i>	35
<i>Figure 17: The sub-product symbol</i>	35
<i>Figure 18: the 'Wait' instruction as a fictive step for managing specific conditions in an AND divergence</i>	35
<i>Figure 19: The 'Wait' instruction as a 'Nothing to do' step according to the conditions in an OR divergence</i> ...	35
<i>Figure 20: Assembly of sub-products</i>	36
<i>Figure 21: Assembly final product representation using referencing of sub-products assembly</i>	36
<i>Figure 22: Dependent tasks in parallel sequences and management by delays</i>	37
<i>Figure 23: The truck assembly training</i>	41
<i>Figure 24: The Assembly Sequences Modeling Language (ASML) built applied on an assembly example</i>	42
<i>Figure 25: The elementary rules for sequences time estimation using an ASML representation</i>	45
<i>Figure 26: Examples of time determination using the ASML representation</i>	46
<i>Figure 27: Example of time estimation of a full Manual assembly sequence</i>	48
<i>Figure 28: Example of time estimation of a full Automatic assembly sequence</i>	49
<i>Figure 29: Example of time estimation of a full Robotic assembly sequence</i>	49
<i>Figure 30: Example of time estimation of a full Manual assembly sequence</i>	50

List of Tables

<i>Table 1: Research tendencies in assembly Mechanical Automation.....</i>	<i>5</i>
<i>Table 2: Research tendencies in assembly Information Automation.....</i>	<i>7</i>
<i>Table 3: Design Guidelines and Rules for Manual, Automatic, and Robotic Assembly (gathered from[102])....</i>	<i>24</i>
<i>Table 4: Literature review in modeling languages useful for Assembly sequences representation.....</i>	<i>30</i>
<i>Table 5: Existent modeling languages and requirements fulfillment.....</i>	<i>32</i>
<i>Table 6: The standardized Assembly Motions.....</i>	<i>39</i>
<i>Table 7: The example assembly operating mode description.....</i>	<i>41</i>
<i>Table 8: The requirements fulfillment by the Assembly Sequences Modeling Language (ASML) built.....</i>	<i>43</i>

CHAPTER 1. INTRODUCTION

1.1. Industry and automation context

The driving objectives of manufacturers for their assembly processes are generally increased rapidity, reliability, and robustness. Their choices were mainly made from a technical point of view. Hill [52] stated that “the major problem with the technology oriented literature is that it focuses on the specific applications and the potential improvements but, unfortunately, fails to explain how to select technological investments that support a business“. This is making manufacturers often opting for a high level of automation that are generally oversized and more productive than required, and not always the most suitable for their production and context. In fact, they are realizing in the last few years that a maximum level of automation is not a guarantee of success, and not a guarantee for better margins for products to sell. In this context Fieldman and Slam [1] point out that: “To be competitive nowadays it is absolutely necessary for manufacturers to align their products and production with customer demands. This customer orientation is leading to an increasing number of variants and to shorter product life cycles requiring a high degree of flexibility”. Brainbridge [37] noted: “In a time of rapidly changing technologies and shortening product life cycles, many companies are focusing on automation as a means for competing on a more demanding market. However, an increased usage of automation does not necessary result in increased benefits”.

In fact, in the last years, and due to mass customized and individualized products, manufacturers should respond to customers becoming more and more demanding in product quality and personalization. Much of quality is related to repeatability and reproducible quality that may be performed by automated processes. Yet, automated processes are not always flexible, adaptive, and convenient to production where high variability in the demand exists. Brainbridge [37] noted in this context: “as demands for more customized products increase and production systems become more and more complex, increased levels and extent of automation do not necessarily result in desired results “.

Thus, production systems and supply chains must be designed to handle on one hand such high variety while at the same time achieve mass production quality and productivity [2]. On the other hand manufacturer should consider and take into account the product market life being shorter and shorter. In this context Ili [3] reported that in the automotive supplier industry, the average lifetime of a component declined 30% from 7.8 years to 5.4 years between 1986 and 2000.

Consequently, the manufacturers’ environment and context becomes more and more competitive and difficult. In order to survive and to secure their position in the worldwide market, they must manage their costs and investments from many points of views and perspectives, especially the product design, the high costs and investments, the product manufacturing and the production processes.

One of the most relevant solutions for every manufacturer used to face the manufacturing cost pressure is to rationalize automation. Automation, when well defined and well dimensioned, allows considerably reducing costs increasing competitiveness, especially in areas where the labor costs and the volume are high. It permits particularly reducing assembly time and cost. In fact, the assembly step are still costly for the reason that it represents between 30% and 50% of overall production time in the automotive industry, and up to 70% in all the industries [4]. Therefore it is evident that the opportunity to reduce the global product cost from the assembly step is worthwhile, and as cited by Ross [5], automation can help to rationalize the assembly.

Consequently, automation can contribute efficiently to improve manufacturing capability and industries position in the world market facing an aggressive globalization and competitiveness.

During the last years, industrial automation is more and more adopted by manufacturers for production systems. According to Lay and Schirmeister [6], the use of automation within factories especially in Germany, has experienced constant growth between 1989 and 1999. Furthermore, the author noted in the same reference that, after having experienced a high level of automation, the results of a survey in German companies about automation shown that more than a third of the 355 surveyed companies planned to reduce the level of automation within their plants. It can be seen basing on these results that automation can be advantageous if we see the two third of companies satisfied, and may also be disadvantageous if we see the

third of the companies which are disappointed and wants to reduce the level of automation. In the same context Boothroyd [95] noted that “although during the last few decades, efforts have been made to reduce assembly costs by the application of high speed automation and, more recently, by the use of assembly robots, success has been quite limited. Many workers assembling mechanical products are still using the same basing tools as those employed at the time of the Industrial revolution”. Therefore we can confirm the existence of a convenient or suitable level of automation for each company that should be defined according to some parameters, and that is what we are defining as “The optimal level of automation”. Recently, and with the evolution of technology and science in fields of automation and robotics, many technical research and studies are being done for improving manufacturing technologies with flexible manufacturing systems and autonomous systems, allowing flexible and reconfigurable systems that are adaptive with the products variation and production variability. However, these systems still expensive, not accessible, and not suitable for the major of companies especially for the small and medium sized industries.

1.2. Deciding about automation

The level of automation for the assembly process should ensure the required production volume in its nominal production rate, without being oversized. Thus, a convenient dimensioning and an accurate study of the required performance and production rate of the process should be done in order to respond to the market demand or the planned volume to produce with the most adequate process minimizing as much as possible the manufacturing cost.

Other involved parameters in the level of automation definition will be considered as product and parts required quality, type, design and characteristics. All these criteria will contribute to the evaluation of the LoA. For example, a part with a thickness inferior than 2mm will be more difficult to hand and to insert, and then an operator will spend more time in assembling it than in assembling a thicker part. A same reasoning is true for a non symmetric part compared to a symmetric because it demands a time to align the part in order to insert it in the correct orientation. This required time differs according to the process level of automation, and then a level of automation may be fixed according to that issue of time saving, because it is affecting the product cost and the profitability. In fact, a profitability study will be done to justify a solution and not the other according to the production volume and context.

As the assembly can differ completely from an environment to another, and in order to build a method allowing judging the LoA for every assembly system similarly whether in an existent assembly system or when designing a new assembly system, a standardization of the assembly description will be proposed in order to unify and simplify the study.

The purpose of this work is to define a standard methodology allowing the decision about automation in assembly lines. This decision will be located between the product design that is supposed to be known, and the process design. The assembly sequence would be needed in the decision and will be supposed to be known. A graphical method would be needed to describe the assembly sequence using elementary assembly motion time assessed, in order to detect pattern and tasks for automation. These standard elementary motions and graphical method will be built and defined in this work, in order to prepare to the decision further.

Other factors should be considered to evaluate the level of automation as product market life, production volume, machines cost for automatic and robotic, and criteria related to the factory itself as its location and labor costs, and also its situation from economical, financial, social, and organizational points of view allowing or not automatic or robotic investments. These factors will not be detailed in this work but may represent important outlooks to improve this work.

1.3. General objectives and purpose of this master thesis

The aim of the work initiated by this master thesis is to help developing a standard method supporting manufacturing deciders and processes conceivers and orienting them in the design step of the assembly machines with the most convenient level of automation. This decision will be built according to relevant involved parameters in the decision such as the product and parts characteristics, the product assembly sequence, the product market life, the production volume, the manufacturing location impacting the labor cost and some other parameters as tasks manually forbidden or the required product quality imposing some task in automatic, the economical aspect and the initial admissible investment, etc.. The method should precise which tasks to execute in manual assembly, in automatic, or in robotic with estimating the time required and the solution cost, in order to argument and to justify the choice and the solution. This tool will be helpful and beneficial since that it will avoid some costly solutions not suitable or feasible for factories.

The procedure and methodology should be generic and applicable for every assembly manufacturer whichever is its product to assemble or its context. In fact the decision procedure should be standard and should take into account the related specific criteria during the decision process using a standard assembly motions with specific timings according to criteria that are specific for the product, and involving all the other manufacturer parameters.

To decision methodology built led to a need to a graphical method dedicated to assembly sequences representation. This led, after a literature review on the existent graphical method usable in assembly, to a new assembly method definition and building,

Therefore, the research process and findings will be introduced, presented and constructed through the following parts of this report:

The chapter 2 entitled “Review, analysis, and limitations of the existent in assembly manufacturing and automation” will consist in state of the art about the actual research orientation and studies in manufacturing, level of automation and the decision about automating.

The chapter 3 entitled “The position of the decision in the manufacturing procedure, Information involved, and the decision basis, tools needed, and outline “ will define the position of the decision in the process, the factors that will be considered, and will present tools on which the assembly decision and methodology to build will be based. The chapter will end by the decision about automation methodology outline presenting a decision making state chart.

In the chapter 4 entitled “A new modeling language building for assembly sequences representation and optimization: The Assembly Sequences Modeling Language”, we will build a graphical method for representing assembly sequences with standardized rules and notions. An assembly vocabulary of motions will be defined and standardized related to the method, allowing describing any assembly operations in industry. These motions will be used in the graphical standard method. The graphical method will be exhaustively presented, defined and argued after presenting the existent methods used in assembly and manufacturing and the need argumentation to a new graphical method building. The benefits and contribution of the new method will be presented comparing to the existent methods. The chapter will be ended by an example of application.

The chapter 5 “Assembly sequence and motions time estimation, analysis, and time involvement in the decision about automation” aims to define rules of estimating assembly sequences represented using the modeling language built (ASML). After rules definition, the assembly standardized motion will be estimated for manual, automatic, and robotic assembly, considering the factors impacting the duration for each motion. Examples of time estimation are presented at the end of the chapter for manual, automatic, robotic, and hybrid assembly for a defined assembly sequence studied in the previous chapter.

In the last chapter entitled “conclusion and outlook” we will conclude the report by presenting the main results and contributions of the work and suggest the project perspectives.

CHAPTER 2. Review, Analysis, and Limitations of the existent in Assembly Manufacturing and Automation

2.1. Introduction

The aim of this chapter is to present a state of the art on level of automation (LoA) and machinery in manufacturing and assembly. The purpose is to present the tendencies and orientation of research in assembly consisting on improving technological processes in assembly manufacturing such as reconfigurable manufacturing systems (RMS), flexible manufacturing systems (FMS), autonomous or advanced manufacturing systems (AMS), and manufacturing support systems. Other tendencies in the domain recently consists on the concept of level of automation (LoA) and some works deal with the decision about automation in assembly and manufacturing.

The part will start by the review of what is the more frequent in the literature of assembly automation that is a focus on improving performance, productivity, and autonomy of production systems and projecting the manufacturing systems on advanced and new technologies of automation, robotics, and feedback sensors rather than the focus on the most adequate production system. The notion of the most adequate production system appeared recently in the last few years with the appearance of the Level of Automation (LoA) aiming to find the most convenient process to a considered factory basing on its own parameters, factors, and context, and that's what will be studied in the second part of this chapter. The third part of the chapter will focus on how decision is made about automation in the literature.

2.2. Tendencies and major research orientations in assembly automation

The focus of researchers in assembly automation is generally technical and concentrated on improving performance, productivity, and autonomy of manufacturing processes.

Besides, the studies concern also the information automation and manufacturing support system automation as will be detailed in this section.

In fact, and as it will be presented in the literature further in the next part, many researchers noted that automation concerns Mechanical automation and Information automation. The first type concerns the machines and the physical processes. The second concerns the information systems, communication, and manufacturing information tools.

Therefore, this review will be divided to:

- Tendencies in assembly Mechanical Automation
- Tendencies in assembly Information Automation

A- Research tendencies in assembly Mechanical Automation

The first appearance and evolution of technological mechanical manufacturing paradigms from Flexible Manufacturing Systems over Reconfigurable Systems towards Autonomous Manufacturing Systems are shown in table 1.

Autonomy in general means the independence of a system in making decisions by itself without external instructions and performing actions by itself without external forces [60].

The Characteristics of autonomy for a system [60]:

- The independence from neighbor systems and from its environment
- The ability to control itself.

Table 1: Research tendencies in assembly Mechanical Automation

Assembly Mechanical Automation										
	Flexible Manufacturing systems (FMS)	Reconfigurable Manufacturing systems (RMS)	Autonomous Manufacturing systems (AMS)							
Appearance	1980s [60]	1990s [60]	2000s [60]							
Market Demand	Variety of products Small volume per product [60]	Customized products Fluctuating demand [60]	Personalized products Turbulent markets [60]							
Requirements	Flexibility	Adaptability, changeability	Self-Adaptability, Self-Optimization, Self-Organization [60]							
Control	Central control system, hierarchical structure [60]	Central and decentralized controls, dynamic structure [60]	Autonomous control, Hierarchical structure [60]							
Description	<p>-The flexibility and adaptability is realized by clustering the assembly system into subsystems and modules which get a certain degree of autonomy and control themselves in a decentralized way (figure 1 Appendix)</p> <p>- The assembly system consisting of a network of assembly stations or cells, buffers, transport systems etc. is clustered into subsystems and modules. These subsystems and modules get a certain degree of freedom to react on changes by themselves and adapt to new demands</p> <p>- they are more or less autonomous [60].</p> <p>-Autonomy in general means the independence of a system in making decisions by itself without external instructions and performing actions by itself without external forces [60].</p> <p>- Advantages:</p> <ul style="list-style-type: none"> * The benefit of introducing autonomous subsystems within an assembly system is reduced complexity of both the physical structure and the information system [66] , flexibility, adaptability, robustness, and fault tolerance. They enable rapid response to customer needs [67]. <p>- Disadvantages:</p> <ul style="list-style-type: none"> *When the control system is a central control system, ''the complexity of such control systems grows rapidly with the size of the underlying 	<p>- Based on decentralised control approaches and heterarchical architectures</p> <p>-The implementation of intelligent control strategies became required in order to adapt the system [1] :</p> <ul style="list-style-type: none"> * The majority of researchers used agents and multi-agent systems either as design metaphor, as software technology or for simulation models [72]. * The Intelligent Manufacturing System (IMS) program and the Holonic Manufacturing System (HMS) concept developed within this program ([73], [74], [75], [76], [77], [78]). <p>A "HMS" consists of distributed, autonomous, cooperative agents or holons. Three basic holons were defined: resource holons, product holons, and order holons [79] (Figure 2 Appendix).</p> <p>- The multi-agent concepts used for decentralized assembly control include both powerful agents with planning and optimization capabilities and simple agents with only a set of rules.</p> <p>-The intelligent agents use planning and optimization heuristics already known from central control systems such as:</p> <ul style="list-style-type: none"> *Genetic algorithms *Neural networks *Fuzzy logic etc <p>-The reconfigurability was realized by building autonomous assembly cells which were connected by flexible transport systems such as automated guided vehicles. An assembly system</p>	<p>- The aim of designing autonomous assembly systems is to reach self reconfigurability by both hardware and software [60].</p> <p>- Only the combination of reconfigurable hardware and software will lead to an autonomous assembly system [60].</p> <p>- The enabling technologies to realize autonomous products are [60] (figure 5 Appendix):</p> <ul style="list-style-type: none"> * Identification (e.g. RFID) * Localization (e.g. RFID reader, WiFi, GPS) * Communication (e.g. WiFi, UMTS) * Decentralized data processing (e.g. software agents) * Sensor networks (e.g. visual sensors) <p>- The more autonomous the assembly systems will be in the future, the more sensors are going to become indispensable [82].</p> <p>- Autonomous machines in assembly are mainly autonomous robots for handling and assembly but also autonomously controlled transport systems.</p> <p>- The works and studies in recent autonomous systems can be divided into:</p> <ul style="list-style-type: none"> * Full-Automatic stations based on an autonomous robot * Cooperative man-robot systems * Automatic multi-robots stations 	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: center; padding: 5px;">Full-Automatic stations based on an autonomous robot</th> <th style="text-align: center; padding: 5px;">Cooperative man-robot systems</th> <th style="text-align: center; padding: 5px;">Automatic multi-robots stations</th> </tr> </thead> <tbody> <tr> <td style="padding: 5px;">Autonomous robots were developed which are able to recognize their environment by sensors, to coordinate their work with other robots and assembly equipment, and to adapt the assembly process if new products had to be assembled. 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manufacturing system. This complexity results in high costs for development, maintenance, operation and modification of the CIM control system. Alternatively, heterarchical control architectures lead to reduced complexity by localizing information and control, to reduced software development costs by eliminating supervisory levels, higher maintainability and modifiability due to improved modularity and self-configurability, and improved reliability by taking a fault-tolerant approach rather than a fault-free approach.” [68], [69], [70], [71].

consisting of flexibly connected autonomous cells can be adapted quickly to changing production volume and product mix.
 -To increase flexibility and adaptability, the cells were built up of replaceable components and modules. The concept of “Plug & Produce” helped to quickly introduce new or remove old units or devices in analogy to the “Plug & Play” concept in the computer world [81]. “Plug & Produce” is defined as the linking of system elements to ready-for-use production systems without manual configuration effort.

Examples of works

-Developed at the beginning of the ‘70s as a research topic and has been adopted as a real application since the ‘80s, pushes for set up times reduction to enable wide mixes of components, exploiting such enablers as robots and machining centers [67].
 - Many works based on the mixed type business model Push-Pull: design-make-sell-assemble dominates this paradigm. The components of the products are still produced following the Mass Production paradigm but they are assembled only after the client has decided some optional [67].
 -Starting in 1983, in Italy the National Research Council has launched such research programs as [67]:
 • The “Targeted Research Programs on Mechanical Technology”, mostly addressing the FMS development and implementation [100]
 • The “Targeted Research Programs on Robotic Systems”, focusing on new robotic systems and applications [101]

-Feldmann et al. developed in 2005 a system of automated guided vehicles (AGV) with distributed, decentralized control [83] (Figure 3 Appendix). The AGVs transport parts and subassemblies between assembly stations and cells whereby they autonomously decide about their particular routes. Each AGV has a control system by its own which realizes not only the routing and control of the AGV but also all decision-making and coordination tasks for the processing of transport orders and collision avoidance. For this, agents negotiate between AGVs and stations in real time. Feldmann et al. ([81], [84], figure 4 Appendix) developed a decentralised, self-organising and “Plug & Produce”-able material flow system which is based on autonomous modules where each module automatically possesses knowledge of all other modules in the system and the way they are coupled.

- Schippner et al. developed the Mobile Autonomous Robot Twente (MART) [86], [87] : The concept of the Mobile Autonomous Robot Twente consists of a vehicle-based 4 degrees of freedom assembly robot, a part supply station, and a navigation system. The mobile robot carries the assembly manipulator and a number of product carriers. Assembly is performed on board. The manipulator is controlled by distributed software that can be downloaded via radio link [87].
 - Fujita presented a human-like assembly robot which autonomously interprets an assembly job by simply observing a sample object and thereby generates a task sequence and action procedure. By following this action procedure, the robot can then assemble a replica of the sample. With the aid of sensors and detailed knowledge of executable tasks, the robot is able to grasp a targeted object which is not precisely placed and securely attach it to a subassembly at the desired position [90].

- Krüger at al. proposed a hybrid assembly cell to overcome the separation of man and robot and to combine the accuracy and speed of robots with the flexibility and reliability of human workers. They developed a system based on digital 3D image analysis which supervises the common working area of robot and man [43] (Figure 6 Appendix).
 - Krüger at al. continued the issue with presenting the robot system "Cobot" capable of sharing the workspace with the human co-worker and collaborating with him through direct physical contact. Intelligent assist systems (IAS) represent a novel class of assembly systems capable of working with human operators [85] (Figure7Apnx)
 - Morioka and Sakakibara [91] presented a project of a new cell production system with a human and robot cooperation. The aim of the system is to make the operator avoid doing mistakes with feeding only components that he needs. It keeps him also concentrated in complex tasks. The system includes a support system explaining to the operator the operations to do. The degree of detail can be controlled according to the skill level of the operator.

- Hirabayashi proposed a system of travelling assembly robots where three sets of robots are moving around on a rail track [87], [88].
 - Hitachi realised an assembly system using automatic guided vehicles (AGVs) which work as part feeders, assembly tools, universal robots etc. This system can change its configuration using a precision autonomous robot system that does not require a teaching process [89].
 - Pelagage et Al [44] presented a study about building criteria for multi robots assembly cells highlighting the difficulties encountered such as the coordination and synchronization, the sequencing, the collision avoidance, and the communication architecture.

B- Research tendencies in assembly Information Automation

This section is focused on the second type of automation “Information Automation” which consists on a real axis of research in the assembly automation and manufacturing. The focus here will be on manufacturing support system and tools researches and domains.

Manufacturing support systems are technologies that enhance the performance of the processes and sometimes they are absolutely essential in order to achieve the full potential of the manufacturing system [23].

The automation of manufacturing support system aims at reducing the amount of manual and clerical effort in product design, manufacturing planning and control, and the business functions of the firm [23].

According to Boyer and Pagell [49], in manufacturing support systems a distinction can be made between design applications, manufacturing applications, and administrative applications

We organize the tendencies in assembly Information Automation as shown in the table 2.

Table 2: Research tendencies in assembly Information Automation

Assembly Information Automation			
	Design applications	Manufacturing applications	Administrative applications
Examples	Computer Aided Design (CAD), Computer-Aided Engineering (CAE) [23]	Computer Aided Manufacturing (CAM) [23]	Electronic mails, knowledge management system, decision support systems, material requirements planning (MRP), and enterprise resource planning (ERP) [23]
	Product life cycle management (PLM): Allows companies to manage the entire lifecycle of a product efficiently and cost-effectively, from ideation, design and manufacture, through service and disposal. Computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided engineering (CAE), product data management (PDM) and digital manufacturing converge through PLM [98] (figure 8 Appendix).		

It can be seen from this technical oriented research of both mechanical and information automation that the dimensioning and decision about assembly processes for a specific installation is absent. In this sense citations were found in the literature that may argue this lack of information:

- Lindström and Winroth stated that « the support for automation decisions is poor » and claimed that « There is clearly a need for developing support tools to find an appropriate level of automation for more efficient and robust production systems » [15].
- Hill [52] stated that the major problem with the technology oriented literature is that it focuses on the specific applications and the potential improvements but, unfortunately, fails to explain how to select technological investments that support a business.
- Ross [5] noted that the discussions on the question to automate or not, are not well documented and the path that lead to the final decision is not traceable.
- Frohm [12] noted from a review that it could be concluded that the usefulness of automation is very much dependent on finding appropriate distribution of tasks between the human and the technical system.
- Parasuraman et Al [25] and Wiener et Al [92] stated that “in contrast to the voluminous technical literature on automation, there is a small but growing research base examining the human capabilities involved in work with automated systems”.
- Säfsten [23] noted that « for the technology-oriented literature a limitation within the human factors engineering domain is that it focuses on the specific applications and does not consider whether different solutions support a business ».

Therefore, during the last few years, some studies are being published about the right dimensioning of the manufacturing process being convenient to a defined manufacturer, with consideration of factors related to the plant itself and its context. A comeback to consider manual execution of tasks if needed was registered. This appeared with the appearance of the concept of the level of automation, some approaches for the evaluation and measurement of the level of automation the most profitable and adequate to a company.

Some questions about the fact of determining the convenient process for a considered plant are being to be asked such as “Which system functions should be automated and to what extent? ” [25] leading to the consideration of both manual and automatic operations and tasks in hybrid systems looking more optimal and more suitable to the specific case of application and taking into account interactions between humans and automated subsystems.

The decision about automating tasks will be based on evaluative criteria leading to what extent automating, and as said by Parasuraman et Al [25] “because the impact of the evaluative criteria may differ between systems, the appropriate types and levels of automation for different systems can vary widely”.

The aim of the next part will be the presentation of works done in the literature in the domain of the Level of automation and the decision about automation in assembly.

2.3. The Level of Automation concept

2.3.1. The Level of Automation in the literature

In the manufacturing domain, the literature and works addressing the level of automation and especially in assembly are not abundant. Besides, the existent works and definitions around this concept are quite different and the definition for this concept is far to be unique or standard.

In the definition of this concept of LoA, several perspectives and points of views exist and many distinctions may be done. We organize the definitions in seven families where each family includes a same global concept or perspective of LoA. These concepts are shown in figure 1 and are detailed below.

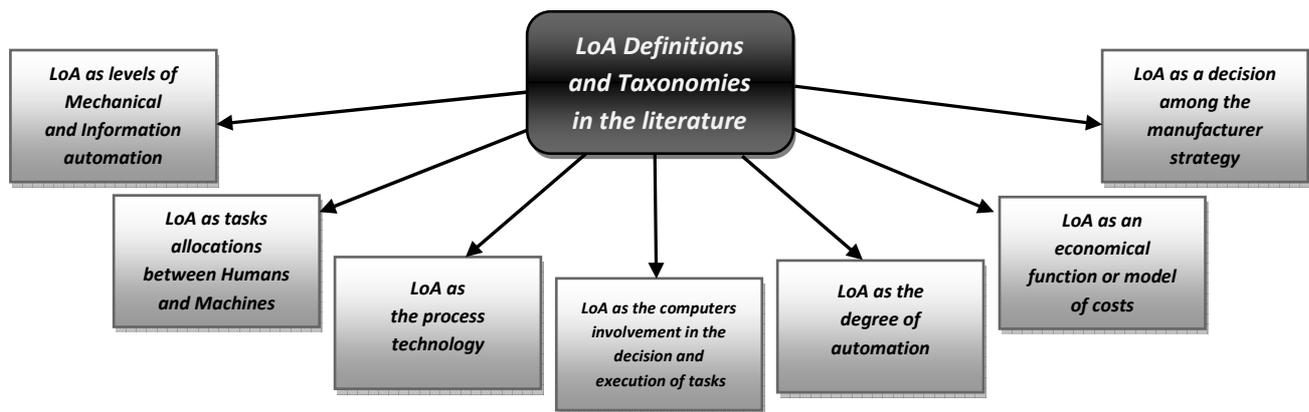


Figure 1: LoA definitions and taxonomies in the literature

A- LoA as levels for Mechanical automation and Information automation

LoA is defined as the allocation of physical (mechanical processes) and cognitive (information or computerized) tasks between humans and technology [12], described as a ranging from totally manual to totally automatic (table 3 Appendix). A seven scale LoA is used to describe each of the two types of automation: the Mechanical LoA as the level of automation for Physical support or mechanical activities, and Information LoA as the level of cognitive (computerized) activities [12]. In another source [13], LoA is defined similarly as a reference to both mechanized and cognitive tasks allocated between humans and technical equipment. Also a range from 1 to 7 is used as an LoA scale. This level of automation is decided from product to product depending on volume and there are no support systems guiding decisions [13].

B- LoA as tasks allocations between Humans and Machines

The LoA was defined as the relation between human and technology in terms of task and function allocation, which can be expressed as an index between 1 (total manual work) and 9 (total automation) [7]. The graduation from 1 to 9 reflects the dominance of tasks allocated to machines in relation to those allocated to humans. In other work, LoA was described also in discrete steps but consisting on manual, semi-automated, and automated depending on task allocation between operators and equipment [23].

This LoA was viewed in the literature as a dimension of process technology consisting of a mix of process technology and humans and stretches between high acuity and judgement and low acuity and judgement. In order to optimize this LoA, manufacturers have to optimize the task allocation between humans and machines because of the complementarities of technology efficiency with the flexibility of humans [15]. In another way and for an LoA optimization sake, task allocation should be optimized by “Allocating to the human the tasks best suited to the human, allocating to the automation the tasks best suited to it” and “Achieving the best combination of human and automatic control, where best is defined by explicit system objectives” [21]. In order to fully utilize the capabilities of both humans and machines in a semi-automated manufacturing system, the interaction between them needs to be well conceived [22]. Such interaction has traditionally been described in human factors engineering in the terms of function allocation, implying a system design process where

functions are allocated to humans or to machines, respectively. The resulting function allocation may be described as the LoA, ranging from entirely manual operations to full automation [22].

A figure about the optimal level of automation (Figure 9 Appendix) called “Rightomation“ was proposed [23] aiming to represent how maximizing the company competitiveness avoiding the under automation and the over automation which both decrease the manufacturer competitiveness, with presenting the advantages and disadvantages for each position of the company. In fact, an appropriate LoA, ‘rightomation’, contributes positively in several aspects, whereas the effects from both under and over automation can have negative effects on manufacturing performance.

The LoA was also defined as the concept viewing automation as a task sharing approach between both the human and technology [20]. Fasth et Al [10] noted that “The assembly system needs to have the “right” levels of automation i.e. an optimal mix between human and technology for each task and operation in the system“.

To conclude, it has been hypothesized basing on these alternatives of LoA definitions that by keeping the human involved in system operations, some intermediate LoA may provide better human/system performance than that found with highly automated systems [30,31]

C- LoA as the process technology

LoA can be defined as the ‘‘process technology’’ and refers only to equipment for production [16][17][18]. This view is however technical as it does not take into consideration the integration of humans and technology

D- LoA as the computers involvement in the decision and execution of tasks

Since 1978, a LoA taxonomy incorporating 10 levels was defined [33] (table 4 Appendix). This taxonomy incorporates issues of feedback (what the human should be told by the system), as well as relative sharing of functions determining options, selecting options and implementing. While this taxonomy can be applied in more general terms, it is instantiated in terms of which agent (the human or the computer) gets or requests options, selects actions, requests or approves selection of actions, starts actions, approves start of actions, or reports actions and has been framed in terms of the teleoperation environment.

A 10 level scale for LoA was also developed (table 5 Appendix) [33] aiming to have applicability to a wide array of cognitive and psychomotor tasks requiring real-time control within numerous domains including air traffic control, aircraft piloting, advanced manufacturing and teleoperations. Four generic functions intrinsic to these domains were identified:

- Monitoring : scanning displays to perceive system status
- Generating : formulating options or strategies for achieving goals
- Selecting : deciding on a particular option or strategy
- Implementing : carrying out the chosen option.

Recently, a new 10° scale for LoA was defined [24][25] where a low level implies mainly manual tasks whereas a high level implies limited or no manual tasks (table 6 Appendix).

E- LoA as the degree of automation

The level of automation can also represent the portion of automated functions of a system in relation to the complete function of the system [8].

In this sense, it was defined as the degree or extent to which an automated, i.e. machine- based, approach is employed [27].

The degree of automation can be described as the level of automation [29]. So the notion of level of automation may be confused with the notion of degree of automation.

Gorlach et al [38] in a case study about evaluation of the LoA in 3 sites of VolksWagen automotive manufactures in order to decide if the LoA should be increased or decreased used a scale of LoA reflecting the degree of automation from 1 to 7 where 1 represents the highest LoA (the most automated or full automated) and 7 represents the full manual.

F- LoA as an economical function or model of costs

Hartmann [9] represented graphical curves of manufacturing costs per unit of product (automation costs, personnel costs, and total costs) in function of the process LoA in a scale of [0,100] % of LoA, and the optimal LoA minimizing the total cost (figure 10 Appendix). He defined the LoA concept with a direct correlation and consequence on manufacturing costs. In fact, and as can be seen in figure 10 Appendix, the personnel costs decrease proportionally to the growing LoA. At a beginning, automation is economically justifiable, total cost is decreasing, and automation cost increases almost linearly. Yet, reaching complete

automation causes the automation cost to increase exponentially while the personnel costs decrease only linearly, indicating a higher total cost.

Recently in 2012, Windmark et Al [28] cited that an “Optimal automation level is important in order to realize a resource efficient manufacturing and achieving a long-term sustainable production“. They presented the LoA (noted x_{af}) after developing a complete economical model for optimizing the LoA in discrete batch manufacturing systems as a percentage including the equipment costs per hour (K_{CP}) and the salary costs per hour (K_D) as follow:

$$x_{af} = \frac{K_{CP}}{K_{CP} + K_D}$$

This ratio x_{af} (the LoA) is termed the automation factor. It varies in value between 0 and 1.0. Production when $x_{af}=0$ is entirely manual, the equipment costs being negligible when $x_{af}=1.0$, it is salary costs which are negligible, production being completely unmanned.

This LoA definition is based on a continuous ration with level varying from 0.0 to 1.0 while all other definition are discrete and in a limited scale generally from 1 to 7 or from 1 to 10. This definition is consequently original compared to previous examples.

G- LoA as a decision among the manufacturer strategy

The link between the Level of automation and the strategic approach of the manufacturer was highlighted in the literature:

- Lindström pointed out that “There is a need for developing tools which support alignment of both strategy and operational levels for reconfiguration of automation levels“ [14]
- Lindström and Winroth noted in [15] that “Within the manufacturing strategy literature, decisions regarding automation and more specifically, levels of automation have traditionally been viewed as a structural decision category within the manufacturing strategy literature“.
- They noted that [15] “Research has shown that alignment between manufacturing strategy and decisions regarding automation are often of an ad hoc nature, i.e. the support for making automation decisions is poor“.
- They pointed out also that “The purpose with the methodology for formulation of automation strategy is to choose an appropriate level of automation which is aligned with the manufacturing strategy of the firm where the measurement takes place“[15].
- They noted the current interest for implicating the manufacturer strategic approach in the decision about automation saying that “Manufacturing automation with strategic implications has become of special interest to both practitioners and researchers“[15].
- They also highlighted the need to build support tools for decision about LoA by saying that “There is clearly a need for developing support tools to find an appropriate level of automation for more efficient and robust production systems“[15].
- LoA according to Groover [26] influences the long-term strategies of the company related to the level of competence and where to locate production. It also influences several output factors such as quality, delivery issues, and flexibility [26].

2.3.2. Limitations of the Level of Automation definitions in the literature

After this literature review about the level of automation concept, it can be seen clearly that definitions of the Level of Automation (LoA) are quite different and various definitions for this concept exist. Each researcher introduces his own perspective about this relatively new concept. In fact, this concept seems to be not yet mature. There is no unique or neither common definition, nor approximately a same definition exists. Generally a discrete scale is used to measure and evaluate LoA with different values generally from 1 to 7 or to 10, some authors make difference between physical and cognitive automations and others not, and some authors defines LoA in a continuous scale recently.

There is a need of a complete and accurate definition for this concept in the research domain permitting later the evaluation, measure and dimensioning for manufacturing processes. Some existent definitions are precise, others are general and do not allow a technical identification and a good description of a process. These definitions don't give idea about the basis of the degree of automation and how many tasks in a whole process are done automatically comparing to those done manually.

Some definitions are too subjective and there are generally no objective criteria defined in order to assess it.

For some definitions a scale of values more or less large for LoA measurement is given, and in others only the concept is defined without an issue to evaluate it.

The research domain in the decision about the LoA needs first a standard and common definition of the LoA concept which unifies the most accurate and reasonable existent definitions, it should give a scale or range of values sufficiently large for accuracy sake allowing a good measure and assessment of the factor of LoA.

The methodology to define and measure the LoA should be objective. The LoA value to obtain using this specific definition and methodology shall be the same for everyone who has to follow the procedure.

In the literature, except Hartmann [9] presenting a cost curve in a scale [0,100]% and Säfsten et Al [23] with the last definition in 2012 defining the LoA as a division whose result falls in the [0,1] range, definitions and scales of LoA in the literature are discrete values and generally including ranges from 3 to 10 scale levels for evaluating the LoA. Nevertheless, it is better to have a continuous range of values or a LoA continuous function in order to be more accurate and more representative, giving a percentage value.

By contrast, evaluating a LoA basing only on salary cost and equipment cost [9](figure 10 Appendix) seems to be not sufficient and many other involved factors have to be considered in such a decision.

For the model defined in [23], when a high automatic process is relatively cheap comparing to the labor cost, the LoA will be low using the formula, but in reality the process LoA is high because the process is highly automated. Consequently, the defined continuous scale seems to be accepted and convenient if the approach of defining the LoA will be performed.

2.3.3. Building a new definition of the Level of Automation

In our work, we propose to build an alternative LoA definition. This LoA is seen in our context from an assembly global process abstraction level. This LoA will be used as an indicator informing globally about the degree of automation describing the assembly process. For us, the Level of Automation represents the portion of elementary tasks executed using machines which don't require a high assistance of humans in those tasks whether automated or robotized in relation to the whole of the production tasks that the production system assumes. An elementary task may be whether manual or automated (using automatic or robotic machine). This LoA ranges on a continuous reference scale from 0% representing a completely manual execution to 100% representing a full autonomously machined using autonomous robots or autonomous automated lines.

When using a standard vocabulary of production tasks description as it will be defined later in the section 4.4.3, the LoA can be described as follow:

$$\text{LoA} = \frac{\text{Number of automated production tasks}}{\text{Total number of production tasks}} \times 100$$

Where the “*Total number of production tasks*” is fixed whatever is the technology (manual, automated, robotic) so a constant number. Therefore optimizing the LoA leads optimize the “*number of automated production tasks*” obtained after selecting each task in a defined technology. In that case obtained LoA is the optimal LoA.

With this definition the LoA reflects the allocation between human and technology in the production system.

At the same time, the optimal LoA is the LoA minimizing the cost per product after respecting the strategic orientation of the manufacturer, considering its context, values, production rules as the ergonomic aspect and tasks forbidden manually, quality engagement, environment respect, location for labor cost and local laws to follow, and its economical, financial, and social status.

To calculate the product cost for each production system many strategic parameters should be recovered, exploited and considered such as salary cost per hour, equipment cost, the initial admissible investment, the product planned production cycle, etc..

The optimal LoA is important in order to realize a resource efficient manufacturing, to achieve a long-term sustainable production, and maximize its competitiveness.

The optimal LoA influences the long-term strategies of the company related to the level of competence and where to locate production

Optimizing the LoA aims to obtain the cheapest production process concept being at the same time the most convenient to the concerned manufacturer considering all its own parameters, requirements, and context.

This concept of LoA that we defined in this section will represent an indicator about the global assembly automation degree. Therefore, the importance is more on the methodology definition than on an overall indicator. In fact, the aim of the topic is the decision about automation and this LoA definition may be an indicator calculable resulting as a consequence from the optimal assembly system reached using a decision about automation methodology.

2.4. Deciding about automation in the literature

In fact, determining the optimal level of automation considering intrinsic and specific factors for the manufacturer such as context, location and type of product remains difficult for companies in industrial sector [5,8,12]. The Literature about the decision is not abundant and the support for making automation decisions is poor [15]. In this context Ross noted [5] in 2002 that the discussion on the question to automate or not, are not well documented and the path to lead to the final decision is not traceable. Hill noted [16] that the perspective about the decision and automation in the literature is technical and fails to explain the selection of appropriate technological investments that support a business.

In the literature, few methodologies about the decision were found. Although, many useful ideas that may be exploited later in the decision making were found and will be presented first. These ideas represent encouraging or discouraging parameters for automating or not. Consequently, all what is related to the decision in the literature will be presented as follow:

- Concepts and ideas about the decision: consists on useful parameters or advices to consider or to take into account for the decision.
- Guidelines and frameworks for the decision: consists on standard methodology. The existent methodologies described in the literature are generally abstract, not concrete, consists only on a reasoning manner and don't consist, as it should be the case, on a method or approach to follow accurately and using exact and mathematical tools in order to converge to a same result.

2.4.1. Concepts and Ideas about the decision in the literature

2.4.1.1. Concepts and Ideas about using (full) Manual or (full) Automated

After a literature review about the decision about automation in the literature, many useful concepts and ideas were found, and that may be used further in the decision methodology to build. We organize these ideas in figure 2.

2.4.1.2. Hybrid systems: a mix of Manual and Automated systems

After presenting concepts about using full manual or full automated processes concerning also robotized systems encouraging or discouraging the choice of opting for a full manual or a full automated, we present in this section the concept of combining these two different kinds of systems in the same process, this consists on hybrid systems aiming to bring benefits from both automatic and manual systems.

These hybrid or cooperative cells combine the accuracy and speed of robots with the flexibility and reliability of human workers [43]. This combination is especially useful for complex assembly and handling tasks [43] (figure 13 Appendix). The balanced combination of manual and automated processes increases flexibility, reduces manufacturing costs, provides high quality and throughput [38].

Concretely in this sense, the result of case studies [38] about optimizing existent levels of automation showed that fully automated as well as completely manual processes are not the optimal in automotive assembly. It was also shown that the fictitiously determined levels of automation consisting of automated and manual stations is a better option if the combined effects of cost, quality and flexibility are considered.

Justifying the hybrid systems, Lindström et Al [15] noted that “research has shown the importance of integrating both humans and technology in manufacturing automation, thus supporting sustainable and robust manufacturing system“. It was also declared that “smart automation, is automation achieved with a human touch” [40].The future of assembly manufacturing was predicted by the increase of inline conveyerised systems and semi-automatic bench-mounted machines [39].

Researches also talked about the notion of the « Human centered automation » which is purported to mean « Allocating to the human the task best suited to the human, allocating to the automation the tasks best suited to it » [41]. Sheridan [41] also stated in this context « Achieving the best combination of human and automatic control, where best is defined by explicit system objectives ». In the same way a model called “MABA-MABA” appeared [53] as “Men Are Better At-Machines Are Better At” (table 7 Appendix).

The reconsideration of manual execution in assembly was discussed and argued by involving a convenient dimensioning of this participation. Bley pointed out that « we have to care for appropriate human participation during planning and execution of assembly » [42]. It is in fact more optimized in some cases, especially in mechanical assembly to use hybrid system base on employee's interventions or also manual operations instead to automate, for the sake of flexibility, reducing complexity, feasibility and economy [1]. In fact, since certain elements involved in production of many types can be particularly difficult and costly to automate, the decision is often made to introduce use of partial automation [54]. Yet, in economic allocation and for equivalent performances, if the cost of technology for automating a function is higher than hiring an operator, the function will not be automated even if there is a technical solution [23].

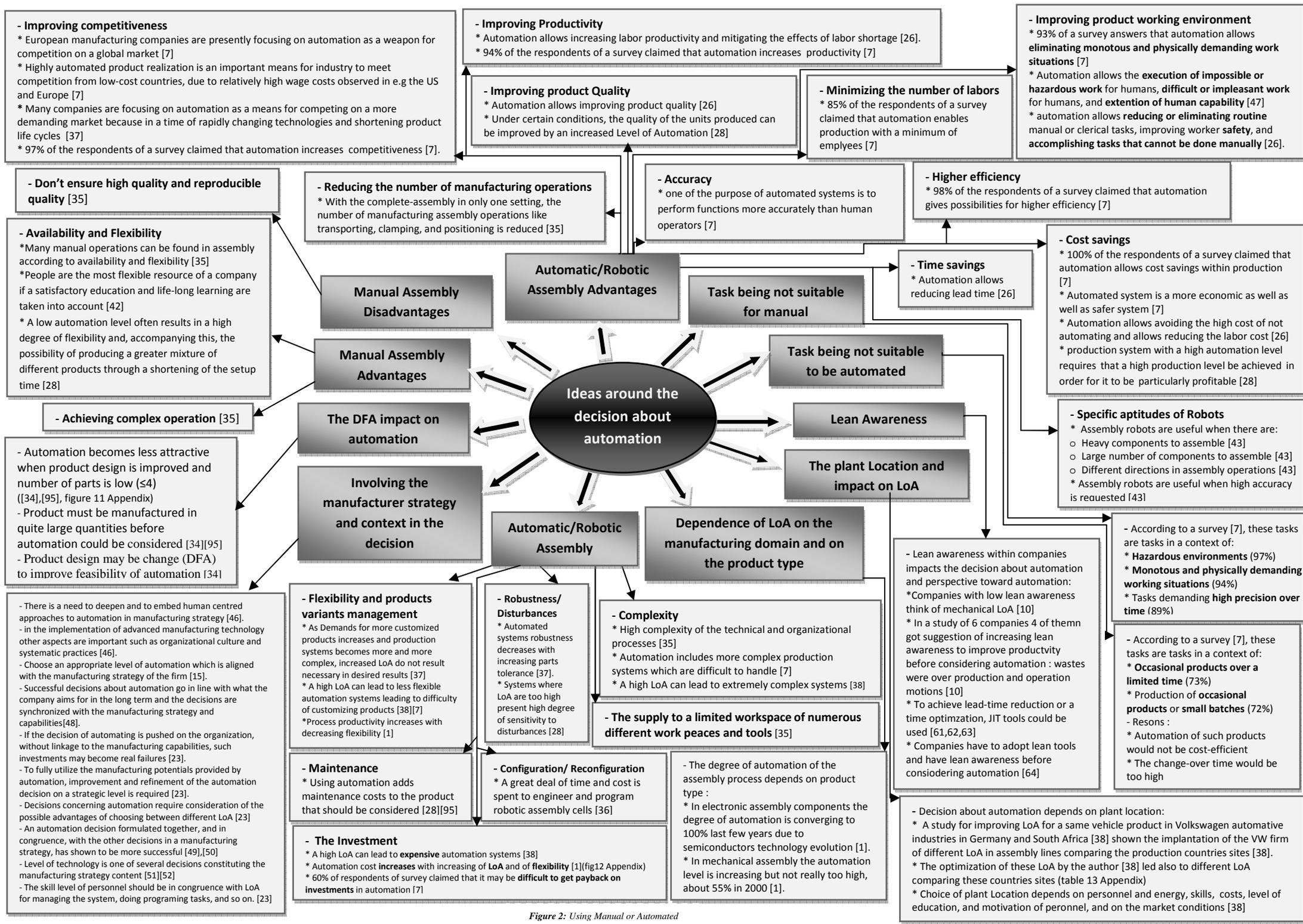


Figure 2: Using Manual or Automated

2.4.1.3. Automation in real cases of manufactories and feedbacks from companies having experience with automation

According to studies done by Fraunhofer Institute, 36% of the companies, which have had experiences with automated solutions, are of the opinion that they exaggerated automation in the past [38].

Evidence from US companies indicates the importance of including human aspects when implementing advanced manufacturing technology [45].

Many studies indicate that most automation decisions emanate from the top, and often the outcome is not what was expected when making the investment [23]. It was also reported that systems in the manufacturing industry are rarely fully automated [23] and a common solution used by manufacturers is to integrate manual and automated operations into semi-automated manufacturing systems [23].

Some case studies were performed and presented by Säfsten [23] about experience of 5 companies with automation in order to study how they worked with automation issues linked to automation decisions. These companies' characteristics are presented in table 8 Appendix. For the results of the experiences please refer to table 10 Appendix. The results indicate that when decisions concerning automation are made without considering the context, the long-term result is not satisfactory.

Kenneth [55] tested and presented an experience of different LoA and process automation in a same application of a case study in the physico-chemical domain and drug research. He tested 5 technologies from the semi automatic process to the robotic and full automated with HTS (High throughput screening) technologies processes aiming the improvements in the capacity, speed and efficiency of the drug discovery processes for a same case study and presented the advantages, disadvantages, capacity and costs of each technology (table 9 Appendix).

Lay and Schirrmeister [6] reported results of a survey in 355 surveyed German companies about automation showing that after having experienced high LoA, more than a third planned to reduce LoA within their plants.

Udo [57] and Mital [58] noted that there continue to be reports of investment failures and difficulties in computer-integrated manufacturing systems implementation, due to the lack of addressing man-machine interaction appropriately.

An important companies' feedback was also reported indicating the need of management to a supported in improving man-machine interaction at the earliest stage of their manufacturing automation decision making process, in order for them to avoid the pitfalls of over-automation which can lead to the failure of computer integrated manufacturing systems to deliver cost-effective and flexible operations [59].

2.4.2. Guidelines and frameworks about the decision in the literature

2.4.2.1. Guidelines and frameworks for conceiving optimal processes

- **Methodology developed by Parasuraman et Al [25]**

- ❖ **The methodology presentation**

Parasuraman et Al [25] developed a decision model (figure 14 Appendix) based on academic literature and industrial surveys aiming to allow designers to determine what should be automated in a particular system. The purpose is to develop a tool that would incorporate human factors in the evaluation of different automation alternatives at the manufacturing systems design stage.

Using the scale defined previously in this report in table 6 Appendix, the authors classified application of automation to 4 classes: Information acquisition, Information analysis, Decision and action, and Action implementation.

Each of these functions can be automated to different degrees, or many levels, and to each class a LoA from the scale is associated (figure 15).

The proposed model provides a framework for examining automation design issues for specific systems.

The evaluation criteria of the decision about automation are organized on a series of steps and an iterative procedure that can be captured as shown in the state chart of figure 14 of Appendix as follow:

- The human performance consequences: Four human performance areas were discussed by the author:
 - *Mental workload*:
Well-designed information automation can change human operator mental workload to a level that is appropriate for the system tasks to be performed.
 - *Situation awareness* :
If a decision aid, expert system, or other type of decision automation consistently and repeatedly selects and executes decision choices in a dynamic environment, the human operator may not be able to sustain a good “picture” of the information sources in the environment because he is not actively engaged in evaluating the information sources leading to a decision.
 - *Complacency* :
If automation is highly but not perfectly reliable in executing decision choices, then the operator may not monitor the automation and its information sources and hence fail to detect the occasional times when the automation fails: -> over trust or complacency
 - *Skill degradation*:
If the decision-making function is consistently performed by automation, there will come a time when the human operator will not be as skilled in performing that function.
- Automation reliability and the costs of decision/Action outcomes
Assessing the appropriate level of automation for decision automation requires additional consideration of the costs associated with decision and action outcomes. The risk associated with a decision outcome was defined as the cost of an error multiplied by the probability of that error.

❖ Discussion and limitations of the methodology

The proposed model suggests the costs as an evaluation criterion, but don't present a methodology to calculate the costs, and don't define thresholds for example to evaluate and compare a solution to others.

The importance, weight, or priorities of evaluation criteria is not discussed.

The model is a simple guide giving an orientation of thinking, but not an accurate methodology to follow allowing precise calculations and a unique solution: it consists on a qualitative approach and not quantitative.

Automation decision may depend on several other evaluation criteria in addition to the proposed criteria.

- Methodology developed by Ross [5]

❖ The methodology presentation

Ross [5] developed a decision methodology (figure 16 Appendix) aiming to determine the economically optimal LoA in the assembly [93].

The inputs of the methodology are the product information like the product range, e.g the quantities that are to be assembled and the description of the parts of each sub-assembly, but also of the assembly processes, e.g type of the joining functions that are used to conduct the assembly processes [93].

The methodology starts by evaluating the technical efforts to economically automate the joining and handling assembly functions of the assembly processes, with the help of a criteria list, which has been created after a literature review by Ross. The output of this analysis is a value called “effort value” for each assembly activity. This effort value is then compared to a threshold value based on previous experiences with automation and stored into a databank. If the effort value is greater than the threshold value, then it is not economically practical to automate the assembly activity and the assembly tasks will be manually done. The decision is consequently argued by an economical feasibility study providing the final output, which is, for Ross, the economically optimal level of automation in a given situation for the assembly [93].

❖ Discussion and limitations of the methodology

The methodology has several advantages such as basing on inputs like product and process assembly that are known at an early stage before the assembly system design. The economic argumentation is also interesting and increases the objectivity of the approach. In addition the method is quantitative and based on calculations.

This methodology has also some limits like basing on few criteria of evaluation which are only technical. In assembly system design several other factors should be considered than the cost efficiency.

Other inconvenient is the inaccuracy of the output: in fact the output is manual or automatic, so 2 only levels of automation are considered, and for the general process. The threshold concept and how to fix it is not detailed nor discussed by Ross, despite it is very important in the decision methodology.

- **Methodology developed by Konold and Reger [94]**

- ❖ **The methodology presentation**

Konold and Reger [94] developed a decision methodology (figure 17 Appendix) giving an indication of the LoA that must be implemented into the assembly system consisting on 4 levels or types of assembly processes [93]:

- Manual assembly where sequence of workstations are not mechanically chained (transfer by hand)
- Manual assembly where sequence of workstations are mechanically chained (automated transfer)
- Hybrid assembly: manual and automatic assembly stations
- Automated assembly: automatic assembly stations

The approach is based on seven questions (figure 17 Appendix) that characterizes the assembly system and covering various domains: the quantities that have to be assembled, the period of time available to the start of mass production, the runtime of the product assembly, the number of product types and variants, the amount of work per assembly, the level of difficulty of the assembly process, and the transfer of the sub-assemblies between the assembly stations.

- ❖ **Discussion and limitations of the methodology**

This methodology presents some advantages as the simplicity, the uniqueness of the result regardless who is the method user, and the applicability of the method at an early stage of the process design seeing the parameters and questions guiding the decisions.

By contrast, the method has some disadvantages such as the output of the method. In fact, the method provides the LoA of the whole assembly system and don't describe accurately which stations to be manual or automated. Solution is not accurate also because don't refer to robotic solution considered also as automated. The aspects to evaluate the LoA consisting of 7 aspects are limited and not sufficient for such a decision. These aspects are also all of them technical and don't involve the manufacturer capabilities such as the economical possibility to invest on an automatic process for example if the decision coming from the methodology is a full automated process which may not be approachable by the manufacturer.

- **Methodology developed by Windmark et Al [28]**

- ❖ **The methodology presentation**

Windmark et Al developed an economic model for determining the optimal level of automation for discrete batch manufacturing. This model is based on several economic equations that the author presented accurately [28]. The economic costs considered involve several product and manufacturing information consisting on: product materials costs, cycle time, downtime rates, rejects, rate losses, material waste, Total material costs of a batch, maintenance cost, salary costs per hour considering the number of operators and the average salary cost per hour, equipment cost per hour, production series size or the batch size, the production setup time, the planned life time of the equipment, the planned renovation of the equipment during its planned lifetime, the basic investment, the cost per year for space the equipment occupies considering the size of the space and the cost per square meter, and other factors.

The author [28] presented, as shown in the part F of the section 2.2.1 in this report, the LoA as a quotient of the equipment costs per hour and the sum of this equipment cost and the salary costs per hour, and presented a formula of the unitary product cost function of this LoA permitting optimizing the cost by deriving this formula with respect to the LoA factor. He presented using the economical equations that he developed the evolution of some manufacturing parameters in function of the LoA (table 11 Appendix). He highlighted by presenting curves that the maximal production capacity and the lowest part costs are not found at same value of the LoA factor (table 12 Appendix). The optimal LoA of system is also also proved dependent on the batch size (table 12 Appendix).

- ❖ **Discussion and limitations of the methodology**

The model seems to be very precise and accurate for calculating the part cost considering many factors that impacts the product cost in the manufacturing, and this model can be helpful in orienting in the methodology building to all factors that can impact the cost of the product, if an economic justification will be followed. Yet, the presented model involves some information and costs that may be not known at an early stage of conceiving a process, such as manufacturing batch size, rejects, rate losses, material waste, and production setup. In fact this model can be helpful in an economic calculation of product cost for a production system to propose, but seems needing an adaptation In order to estimate some costs that cannot be known at an early stage when designing a manufacturing process. From another side, only an economic justification is not sufficient for a decision making about automation, and other factors involving the manufacturer and the product characteristics should be considered.

- **Methodology developed by Boothroyd [95]**

- ❖ **The methodology presentation**

Boothroyd studied in his book “Assembly automation and product design” [95] the assembly manufacturing of an example of a product consisting on a power plug (figure 18 Appendix) and presented a study about the most convenient process to assemble it: The assembly system being the most profitable presenting the least product assembly cost per unit.

The author calculated in the study the cost per part for six different systems: A full manual, two automatic systems: the first using indexing machines and the second using free-transfer machines, and 3 robotic systems: the first using a one-arm robot; the second using two-arm robot; and the last using a multi-station robots.

For each possible assembly solution the author calculates the unitary product assembly cost using economic formulas that he developed previously in this book based on the required feed rate and estimating number of feeders to use, the time estimation using the handling and insertion codes and times according to parts dimension and characteristics developed by Boothroyd [95] for manual, automatic or robotic systems corresponding to the studied process, the feeders costs, estimations of basic machines cost (feeder machine cost estimated to \$7K, indexing machine cost estimated to \$10K, automatic assembly station estimated to \$30K, robotic SCARA standard one arm robot cost estimated to \$80K, robotic two arm robot cost estimated to \$150K), the assembly labor rate in cent/sec (the value used is 0.83 cent/sec (\$30/hr) for the worker labor rate and 1.1 cent/sec for the assembly technicians), the efficiency value (estimated to 80%), tools costs for inspection estimated to \$10K, fixture costs estimated to \$12.5K, the cycle time for each type of station, etc..

The author [95] calculated the cost per part for each assembly system and presented a table comparing the obtained final product assembly costs in order to determine the most profitable assembly system ensuring the least value of product assembly cost (table 14 Appendix).

- ❖ **Discussion and limitations of the methodology**

The economic justification is based on significant information and estimations concerning the product and its characteristics related to the specific assembly system especially from required assembly timing point of view, which reflects the assembly cost. Consequently, this information can be known or estimated at an early stage of the design of an assembly system. And the economic procedure seems to be important and useful.

By contrast, the approach doesn't concern hybrid systems that can be convenient and less costly than the studied processes. In fact, being limited to some specific systems without combinations may don't lead to the most optimal and feasible for a case study.

The standardized costs used such as machine costs may lead to faulty results. In fact, there is sometimes a great difference in prices between automatic machines themselves or between robots themselves according to accuracy, tolerance, domain... Although the author used a standardized cost for automatic, a standardized one of a one arm robot, another for a two arm,.. This issue may be improved by making some categories in machines and in robots based on cost average, range, or order of magnitude.

Other drawback may be cited consisting on limiting the decision making to only the manufacturing cost. This manufacturing cost is important in the decision by is far to be the only criterion. In fact, the most profitable process may be for example not able to ensure for example a required quality, or a competent labor may not be available where the plant is located if the solution is a full manual. Other example, if this approach leads to multi-station robot systems, the economic status of the manufacturer may not allow to purchase or support it.

- **Methodology developed by Almannai et Al [59]**

- ❖ **The methodology presentation**

Almannai et Al [59] developed a decision support tool based on the “Quality Function Deployment” (QFD) technique and the “Failure Mode and Effects Analysis” (FMEA) technique (figure 19 Appendix).

Rather than the traditional investment justification process, the proposed methodology uses the QFD technique as the prime method to link the automation investment objectives with technology, organization, and people evaluation for the selection of the best alternative [59] followed by deployment of the FMEA technique to draw attention to any problems or risks that might be associated aiming to support management in identifying potential problems with the selected alternative and preventing them [59].

In order to be applicable to processes development, modifications and adaptations were mandatory for the QFD and FMEA techniques which are originally relative to products development rather than processes development.

The decision algorithm consists of 3 stages as shown in the figure 20 Appendix: The first consist on weighting the criteria regarding the “management requirements/objectives” using the QFD technique. The second consists on evaluating the automation alternatives regarding the sub-evaluation criteria, in order to identify the most suitable automation alternative using also the QFD. By taking into account the weights of the different criteria classes, a global score is computed for each alternative making possible to rank the alternatives from the best to the worst. The process of identifying the evaluation criteria and sub-evaluation criteria involves compiling a list of the elements that could be related to technology, organization, and people in manufacturing systems selection and design literature. And the third and final stage aims to identify the risks and potential failures associated with the best alternative selected by applying the FMEA technique on this selected process.

❖ Discussion and limitations of the methodology

Giving a quantified approach for evaluating alternatives can be considered as an advantage. Other advantage consists on the fact of basing on strategic information in the evaluation making the method applicable in early stages of designing new processes.

Yet, the methods don't seem very useful and disadvantages also exist for this method such as the definition of the automation alternatives was not defined. In addition, the QFD and FMEA techniques dedicated to product development and adapted by the author for process development was not justified and argued. The validity of adapted QFD in the literature is also not abundant. Other disadvantage is the evaluation criteria which are not fixed but depend on the decision makers and his knowledge, so the method is almost subjective.

2.4.2.2. Guidelines and frameworks for optimizing existent processes

• **The USA (“Understand-Simplify-Automate”) principle**

❖ The methodology presentation

The USA principle («Understand, Simplify, Automate»), is an automation strategy focusing on aspects to consider prior during implementation of automated processes is suggested by Kapp [96]. It is based on an automation migration strategy of an existent process consisting on a plan for evolving the manufacturing systems used to produce new products as the demand grows. It involves three phases: manual production, automation of single stations, and finally automated integrated production [96]. The USA principle was defined by Singh [97] as a common sense approach to automation projects.

The USA is based on three major steps [97]:

- Understand the existing process

The obvious purpose of the first step in the USA approach is to comprehend the current process in all of its details and ask questions such as: What are the inputs? What are the outputs? What exactly happens to the work unit between input and output? What is the function of the process? How does it add value to the product? What are the upstream and downstream operations in the production sequenced, and can they be combined with the process under consideration? [97]

Mathematical models of the process may also be useful to indicate relationships between input parameters and output variables. In this way other questions may be asked: What are the important output variables? How are these output variables affected by inputs to the process, such as raw material properties, process settings, operating parameters, and environmental conditions? This information may be valuable in identifying what output variables need to be measured for feedback purposes and in formulating algorithms for automatic process control.

- Simplify the process

Once the existing process is understood, then the search can begin for ways to simplify. This often involves a checklist of questions about the existing process. What is the purpose of this step or this transport? Is this step necessary? Can this step be eliminated? Is the most appropriate technology being used in this step? How can this step be simplified? Are there necessary steps in the process that might be eliminated without detracting from function? Can steps be integrated into a manually operated production line?

- Automate the process

Once the process has been reduced to its simplest form, then automation can be considered.

❖ Discussion and limitations of the methodology

The USA principle is a methodology that can be helpful in simplifying and automating existent process. But this method doesn't give the tools to apply exactly and concretely. It consists on a logical approach leading to simplify the process after understanding it and can lead to automate it and to reduce cost, but still quite abstract from technical point of view. There are also no parameters to follow or to improve.

• **Methodology developed by Lindström and Winroth [15]**

❖ The methodology presentation

Using the scale LoA described in table 3 Appendix based on mechanical and Information LoA, and in extension of the Swedish Dynamo and Dynamo++ projects, Lindström and Winroth [15] presented a methodology of LoA improvement involving the manufacturer strategy. The purpose is to align LoA with the manufacturer strategy. The proposed methodology consists of four phases:

• Phase 1: developing the methodology for measuring and assessing levels of automation

Done through 8 steps and may be summarized in the main following actions: visiting days to manufacturer and locate what areas should be in focus, doing a pre-study to identify and document the purpose of the production flow and where it starts and ends, identifying and documenting products and variants produced within the production flow, identifying the work organization and the purpose of the machines and humans, identifying and documenting the main task of each section/cell followed by identifying the sub-tasks by observation, using the operations instructions, company documentation using the Hierarchical Task Analysis (HTA) technique, judging the LoA for each task basing on how the task is conducted, and what type of interaction that is observed for fulfilling the task, estimating with the operator or/and production technician on-site the relevant maximum and minimum LoA for each measured task, and analyzing the collected data from the LoA-measurement on-site, with the assessed data on relevant maximum and minimum of LoA [15].

• Phase 2: Validating the dynamo methodology

The purpose with the validation was to perform the whole Dynamo methodology at an industrial company, which had not been participating in the development of the methodology (figure 21 Appendix)

• Phase 3: Reviewing and evaluating manufacturing strategy formulation processes

In this phase the steps taken to review literature on corporate-, business-, and manufacturing strategy formulation processes are described. The objective with the analysis was to identify and describe patterns of the frequency of each criteria used for evaluation of the processes. By doing the analysis, improvement areas were sought and found for improving formulation processes.

• Phase 4: Embedding the measurement methodology in the process of manufacturing strategy formulation

The methodology for formulating automation strategy contains five sub-processes as follow:

- *Preparation*: aiming to agree on purpose of executing the methodology and to make an execution plan.
- *Sub-process 1*: Formulation of business and manufacturing strategy: aims to the assessments of business and manufacturing strategy with the intended purpose and to understand the chosen and intended strategy.
- *Sub-process 2*: Measurement of levels of automation for critical sub-tasks in a production flow.
- *Sub-process 3*: Linking level of automation and strategy: done in the form of a workshop with active participants who take part in the analysis of different LoA alternatives. Moreover, actions should be listed to propose those that are line with the intended manufacturing strategy and also check the outcomes of sub-processes one to three to ensure quality of outcomes and should also provide a plan for implementation of the chosen LoA that is in line with intended strategies.
- *Sub-process 4*: Documentation of the results found in sub-processes

❖ Discussion and limitations of the methodology

This methodology based on Dynamo and Dynamo++ projects has the advantage of the use of its LoA scale which is simple and understandable, and making difference between mechanical and information LoA.

The disadvantage of the methodology consists on the fact of being abstract when speaking about strategy; the methodology is not accurate in terms of which factors to consider for the evaluation, the costs and the economic factor is particularly not discussed. The methodology is not quantitative and this constitutes a real disadvantage.

- **Methodology developed by Fasth and Stahre [10]**

- ❖ *The methodology presentation*

Using the LoA described in table 3 Appendix, and in the context of the Swedish Dynamo projects, Fasth and Stahre [10] defined a methodology for measuring and improving LoA of existent systems within manufactories.

In the first step consisting on the pre-study, information about the production would be gathered and measurement of current stage of LoA should be accomplished basing on observation and interviews. The triggers of changing the situation for the studied companies coming from the companies themselves should be investigated. Investigation around the Lean awareness within these companies should also be performed, in order to verify further their triggers. The aim is to verify if the improvement can really be achieved by applying what they suggest, or the improvement can first be performed by improving lean approach in order to reduce the assembly time and reducing consequently the manufacturing cost. These triggers of change and the current situation of the manufacturer represent the inputs.

The following analysis steps defined by the methodology [10] aims to analyze the possible improvements solutions and to determine if assembly system LoA needs to be changed:

- Step1- Work shop to decide min and max values

The workshop starts with a short briefing on the earlier steps and then if the companies have some triggers of change to redesign their system, which LoA do they think reasonable to have in the new system (fig22 Apndx).

- Step 2- Design a Square of Possible Improvements (SoPI)

The step 1 results are transformed into the LoA matrix to illustrate and to be able to analyze the results. The min and max values form the boundaries for the Square of Possible Improvements (SoPI), shown in (fig23Apx)

- Step 3- Analyse the SoPI

The SoPI is the used tool in order to analyze if it is possible to do a task and/or an operation optimization.

The result of the methodology application on a case study was, as shown in figure 24 Appendix, the need to increase the cognitive level of automation in almost all tasks, and also to increase the mechanical LoA in some tasks.

- ❖ *Discussion and limitations of the methodology*

This methodology has a major advantage consisting on the consideration of 2 aspects of automation: the mechanical LoA (the physical processes) and the information LoA (the cognitive aspect). The simple scale of 7 steps is also simple and easy to use.

The method has also some disadvantages. In fact the design and the analysis of the square of possible improvements are not detailed and the way to compare different LoA and to decide about the right LoA to adopt is not discussed. Argumentation of the LoA and criteria of decision are also not enough studied.

- **Methodology developed by Gorlach and Wessel [38]**

- ❖ *The methodology presentation*

Gorlach and Wessel [38] analyzed the assembly lines of VolksWagen AG at the three production sites (2 sites in Germany and 1 site in South Africa) in order to give recommendations to automate or de-automate by combining aspects of manufacturing systems such as costs, productivity, quality and flexibility. The LoA scale used is a 7° scale where '1' is a full automated and '7' a full manual.

In the methodology, the authors gave an economic justification for the solutions, and to do so, relevant cost approach is used, where only the costs that make the largest contribution are taken into account basing on Ross approach [5]. They considered the following costs types as necessary for the realization of the assembly process: the Personnel (persons who are carrying out and planning activities in the assembly process; personnel costs consist of wages or salary and social costs; depending on personnel qualification), the operating material (installations for assembly and transport; operating material costs include all costs for running the operating material), the material (only consumables are relevant), and the Information cost. The used economic formulas allowing the calculation of the costs are described [38].

The unit assembly cost is considered as a criterion in the decision about the required LoA that the manufacturer has to possess. The other criteria used to evaluate the LoA, besides the cost, are the quality, the productivity, and the flexibility. These criteria are used for determining the best LoA of the assembly systems at the three production sites defined. The optimal level of automation regarding the cost is the level leading to the minimum unit cost [38](table 15 Appendix).

The quality criterion is assessed was based on quotas and indices of number of rejects, of rectification of rejects, of customer complaints, or audit notes. The optimal LoA regarding the quality is based on collected data involving the quality factor in the 3 different sites. The table 16 Appendix shows the quality check and comparison for the three production sites.

The productivity is measured by the number of units that are planned to be and that have been built, the production times (cycle times, manufacturing times, downtimes, total working times), and the number of employees involved in the production process. This information is being set in relation with: the availability of production system, the decreasing degree of performance, the degree of quality, the effectiveness of equipment, the productivity which refers to the average number of vehicles built by one employee during a specified period of time and the number of vehicles built by all employees per hour. The productivity figures are examined in relation to the number of workers. These workers are later seen in relation to the vehicles built and the time needed for that as shown in the figure 25 from which it can be clearly concluded that highly automated is also highly productive when considering that the smallest number of employees produces the highest number of vehicles.

The flexibility is measured by a focus on two aspects: the variations of production quantities and the number of workers required. The most flexible production system considered as the one that has to change the least to cope with the increase/decrease of production quantities, i.e. a minimum variation in the number of workers. The optimal level regarding the flexibility is the level leading to the least variation in number of workers through the $\pm 20\%$ of variation in the product quantity. Table 17 Appendix shows the results: The bold and shaded fields show the most flexible production system with little or no variation in the number of workers, while the underlined fields represent the least flexible production systems with a large variation in the number of workers needed to accommodate different production quantities.

The decision about the optimal LoA involves the 4 criteria. The cost criterion is defined as the basic or main criterion. The other criteria are compared with the LoA of costs to find a total solution for each production site as shown in table 18 Appendix. When an LoA according to a criterion x less prior than another y, the criterion y is scarified and not respected. Sometimes a compromise should be done and a solution where a criterion is not important is not satisfied may be admitted. For example in the table 18 Appendix for the manufactory 'Golf A5 Uitenhage' for the assembly part 1 (AP1), the LoA required regarding the cost is '5', the LoA regarding the quality is '3', but the optimal LoA recommended is '5' (more manual than what the quality requires).

❖ Discussion and limitations of the methodology

The methodology represents many advantages explained by being realistic, concrete, and significant. The 4 criteria considered (cost, quality, productivity, and flexibility) are very convenient and relevant.

A drawback of the method presentation consists on how the value of LoA was fixed concerning the productivity/Flexibility or also other criteria using the gathered information; this is not treated in the article.

Another drawback of this approach consists on how fixing an optimal LoA basing on the 3 values of LoA. This was not argued or studied in the article. In fact, a weighting approach by fixing a coefficient or weight relative to each criterion may be suggested.

After improvements of this method considering these remarks and some adaptations, this technique may be useful for enhancing LoA of existent processes, or may be adapter or exploited in order to create a methodology for optimal LoA determination for new systems conception.

2.5. Conclusion

In this chapter a deep literature review was presented about the actual and recent major studies, orientations, and tendencies of the research in assembly automation where the topic was proved technical and looking to improve productivity without regard to dimensioning the most suitable assembly system for a considered manufacturer. In fact, after a literature review around the concepts of LoA and of the decision about automation, there are considered information in the domain but generally not directly focused on the subject. Many ideas may be exploited particularly in the section concepts and ideas about the decision, which looks helpful for finding the relevant parameters in the decision. The decision methodologies in the literature are far from considering all the relevant factors involving the manufacturer itself, few works had this orientation but are not exhaustive in the decision process and criteria, and no satisfactory methodology that may be applied in manufacturer real decision context exists. There is also no objective algorithm to apply systematically and leading to a same result in a same context without subjectivity and dependence to the decider itself and his own thinking and analysis. In the next chapter, the work around the decision methodology to build will be introduced by the criteria to consider in the decision, and an outline of the decision algorithm will be presented.

CHAPTER 3. The position of the decision in the Manufacturing procedure, Information involved, and the decision basis, tools needed, and outline

3.1. Introduction

The chapter aims to present globally the decision methodology to propose for the optimal level of automation (LoA) determination after the literature review presented in the previous chapters where the existent about LoA from definitions and decisions points of views were presented. In this chapter, the judged interesting concepts encountered in the literature will be considered, combined, and improved in order to build a satisfactory decision methodology that should be accurate, objective as possible, and standard for assembly manufacturing.

The chapter will start by presenting the position of the decision about automation in the manufacturing process and presenting the basis of the methodology to build. Then, some relevant needed tools that will be exploited will be presented consisting on Design For Assembly (DFA), motions and time standards building and Methods Time Measurements (MTM). The criteria involved in the decision considered in the decision methodology will be presented during this chapter which will finish by the outline summarizing the decision mechanism and the general algorithm.

3.2. The position of the decision in the Assembly Manufacturing procedure

3.2.1. Position with regard to product design

Before starting with the decision building, it may be useful to localize this decision making about automation in the manufacturing process and to detect the eventual interaction with the involved members. Globally, the decision is located in the phase between the product design and the process design. In the simplest way it is located after product design and before the process design, preparing and helping process designers. Yet, some interactions may exist with the product designers in order to make manufacturing easier (figure 3).

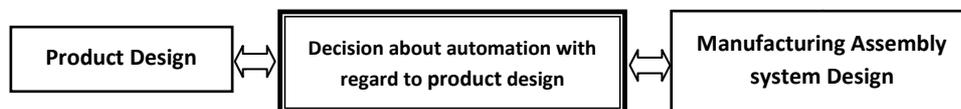


Figure 3: Position of the decision about automation with regard to product design

In fact, there are more and more collaborations between product designers and product manufacturers for the ease of manufacturing. The product design in a modern approach is done with regard to manufacturing and with a design manufacturing collaboration. The product design may be changed or improved to make the manufacturing feasible, easier, or cheaper. Similarly, when designing the manufacturing system, there may have some feedbacks and returns from system designers if difficulties exist or for feasibility issue imposing negotiations with LoA deciders or with product designers for the need of decreasing or increasing LoA (figure3). With these interactions and feedbacks, the traditional attitude of designers “We design it, you build it” or “the-over-the wall approach” [95][102] (figure 4) is being to be completely surpassed in actual manufacturing especially with the appearance of the Design for Assembly (DFA) approach which aims to the ease of manufacture [102] and improving product “assemblability” and “producibility” [103]. In this context Boothroyd noted that “a competent designer should be familiar with manufacturing processes to avoid adding unnecessary to manufacturing costs during design” [102].

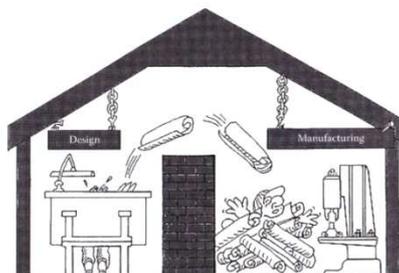


Figure 4: The over the wall design [102]

In addition to the DFA approach which defined rules for the ease of assembly (table 3), time standards was also developed in the 20th century with the Methods-Time Measurements (MTM) approach [104]. These approaches were resumed later by Boothroyd [95][102] who developed rules and standards for DFA and time standards for assembly handling and insertion considering the parts characteristics. These approaches of time standards for motions timings determinations and DFA will be exploited and will form a basis for the decision methodology in order to estimate the assembly sequence motions times for the manual, automatic and robotic technologies which will form one of the axis in the decision as it will be defined later with the decision methodology.

As the MTM and DFA particularly for assembly time standards will be exploited in the decision methodology, contribute actively in the decision approach, and will be present in the position of the decision about automation in the manufacturing process, it will be worthwhile to present these concepts:

3.2.1.1. The Design for Assembly approach

The Design for assembly (DFA) is a process by which products are designed with ease of assembly in mind [105]. The DFA methods can be described by: reducing product part count, improving the modularity of the assembly, utilizing standard part wherever possible, and minimizing the probability of assembly failures [103] (figure 5).

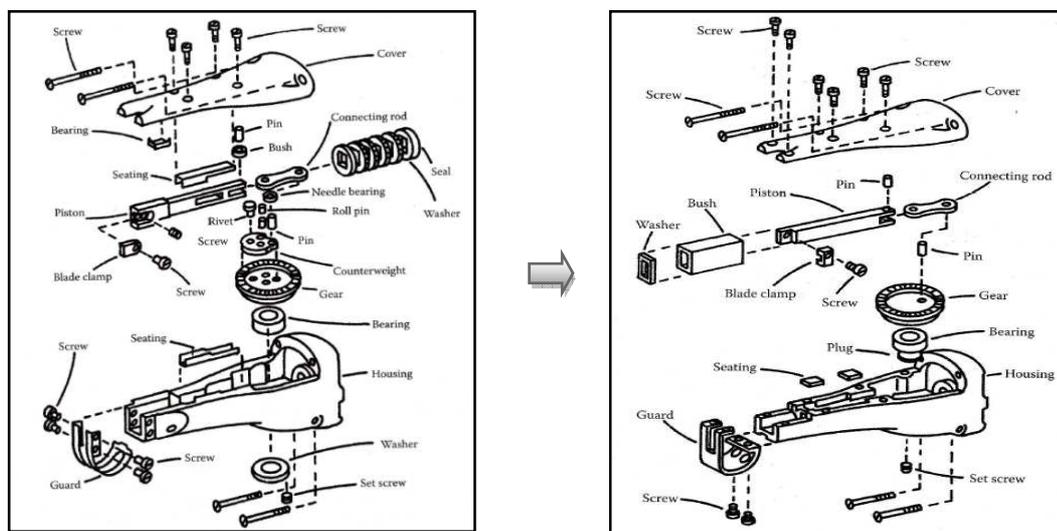


Figure 5: Applying DFA for a same product case [102]

DFA aims also the reduction in assembly cost and product cost noting that product simplification brought about DFA analysis often leads to parts cost reductions that are significantly greater than the reductions in assembly costs [34]. DFA may be applied even when assembly costs are small [34].

The DFA approach is recently related to the assembly system technology (figure 10 Appendix). In fact, the analysis of a product design for ease of assembly depends to a large extent on whether the product is to be assembled manually, with special-purpose (automation), with general purpose automation (robots), or a combination of these [102]. The way to automate or not may be supported by the DFA approach. It was noted that assembly automation becomes less attractive and more difficult to justify as a product design is gradually improved (figure 10 Appendix) [34][95].

Boothroyd [95][102] developed guidelines and design rules for DFA according to the manufacturing technology dependently to manual, automatic, and robotic assembly (table 3). He also developed for each technology time standards for assembly handling and Insertion allowing the assembly time estimation from the early design phase presenting tables with coding or digits determination according to part characteristics: row digit and column digit for each criterion for each part to assemble in order to retrieve the correct corresponding estimated time. Here also a distinction is made between manual (figures 44, 45 Appendix), automated (figures 46,47,48,49 Appendix), and robotic (robotic single station one-arm (figure 50), robotic single station two-arm (figure 51), and robotic multi-station (figure 52)). The assembly handling in the Boothroyd vocabulary consists on acquiring, orienting, and moving the parts, while Insertion (and eventually fastening) consists on mating a part to another part or group of parts [102]. It can be seen that part design symmetry has a principal impact on time required.

Table 3: Design Guidelines and Rules for Manual, Automatic, and Robotic Assembly (gathered from [102])

Design for Assembly Guidelines and Rules	
Manual Assembly	
Rules for part handling	Rules for Insertion and fastening
<ul style="list-style-type: none"> - Design parts that have an end-to-end symmetry and rotational symmetry about the axis of insertion. And if not possible then designing parts having the maximum possible symmetry. - Design part obviously and clearly asymmetric if it cannot be designed symmetric. - Provide features that prevent jamming of parts. - Avoid features that allow tangling of parts when stored. - Avoid parts that stick together, that are slippery, delicate, flexible, very small, very large, that are hazardous to the handler. 	<ul style="list-style-type: none"> - Design so there is little or no resistance to insertion, - Provide chamfers to guide the insertion of two mating parts, - Standardize by using common parts, processes, and methods. - Use pyramid assembly: progressive assembly about 1 axis of reference. - Avoid the necessity to maintain manually parts orientation during manipulation or during the placement without guidance. - Design so that a part is located before it is released. - Take into account the mechanical fastener cost. The classification according to the cost of fastening techniques from the least to the most expensive is as follow: snap fitting, plastic bending, riveting, and screw fastening. - Avoid repositioning the partially completed assembly in the fixture.
Automatic Assembly	
Rules for product design	Rules for design of parts
<ul style="list-style-type: none"> - Minimize the number of parts - Ensure that the product has a suitable base part on which to build the assembly - Ensure that the base part has features that enable it to be readily located in a stable position in the horizontal plane - If possible design the product so that it can be built up in layers, each part being assembled from above and positively located so that there is no tendency for it to move under the action of horizontal forces during the machine index period. - Try to facilitate assembly by providing chamfers or tapers so that help to guide and position the parts in the correct position. - Avoid expensive and time-consuming fastening operations, such as screw fastening, soldering,... 	<ul style="list-style-type: none"> - Avoid projections, holes, or slots so that cause tangling with identical parts when placed in bulk in the feeder. This may be achieved by arranging the holes or slots to be smaller than the projection. - Attempt to make the parts symmetrical to avoid the need for extra orienting devices and the corresponding loss in feeder efficiency. - If symmetry cannot be achieved, exaggerate asymmetrical features to facilitate orienting or, alternatively, provide corresponding asymmetrical features that can be used to orient the parts.
Robotic Assembly	
<ul style="list-style-type: none"> - Reduce part count - Include features such as chamfers, leads, lips, and so on, to make parts self aligning in assembly. - Ensure that parts which are not secured immediately on insertion are self-locating in the assembly. Holding down of unsecured parts cannot be carried out by a single robot arm so special fixturing is required which must be activated by the robot controller, and this adds significantly to special purpose tooling and, hence, assembly costs. With a two-arm-single-station system, one arm can, on principle hold down an unsecured part while the other continues the assembly and fastening processes. - Design parts so that they can all be gripped and inserted using the same robot gripper. One major cause of inefficiency in robot assembly is the need for gripper or tool changes. Each change to a special gripper and the back to the standard gripper is approximately equal to two assembly operations. - Design products so that they can be assembled in layer fashion from directly above. The simplest, least costly, and most reliable 4 degree of freedom robot arms can accomplish the assembly tasks. - Avoid the need for reorienting the partial assembly or for manipulating previously assembled parts. These operations increase the robot assembly cycle time without adding value to the assembly. - Design parts that can be easily handled from bulk. To achieve this goal, avoid parts that: nest or tangle in bulk, are flexible, have thin or tapered edges that can overlap or “shingle” as they move along a conveyor or feed track, are so delicate or fragile that recirculation in a feeder would cause damage, are sticky or magnetic so that a force comparable to the weight of the part is required for separation, are abrasive and will wear the surfaces of automatic handling systems, are light so that air resistance would create conveying problems. - If the parts are to be presented using automatic feeders, then ensure that they can be oriented using simple tooling. Feeding and orienting at high speed is seldom necessary in robot assembly. - If parts are to be presented using automatic feeders, then ensure that they can be delivered in an orientation from which they can be gripped and inserted without any manipulation -> avoid the situation where a part can only be fed in one orientation from which it must be turned over for insertion. - If the parts are to be presented in magazines or part trays, then ensure that they have a stable resting aspect from which they can be gripped and inserted without any manipulation by the robot. 	

3.2.1.2. The Methods Time Measurements approach

Methods-time measurement (MTM) is defined as a tool for helping to engineer a method before beginning production [104]. It allows treating methods and time simultaneously instead of separately and aims increasing objectivity of the existing methods tools and forms an added tool for method engineer [104]

The MTM is a procedure developed for manual assembly analyzing any manual operation or method into the basic motions required to perform it and assigns to each motion a predetermined time standard which is determined by the nature of the motion and the conditions under which it is made [104].

The procedure of collecting data in the MTM is industrial investigations procedure and analysis procedure of motion picture films using three different methods: micro motion study film analysis, “time and motion study and formulas for wage incentives” or Gilbereth basic elements.

Each motion in method time data is classified to classes or cases according to the type or characteristics of the motion or of the assembly operation and to each case or combination/correlation of cases corresponds a time standard value. These standard timings for assembly concerns the following assembly motions that are studied in the MTM procedure (figures 53, 54 Appendix): “Reach”, “Move”, “Turn” (including apply pressure), “Grasp”, “Position”, “Disengage”, and “Release”. An additional motion consisting on “Walking” is presented apart in a curve of time per foot function of worker age and weight (figure 55 Appendix).

3.2.2. Position with regard to Assembly Sequence

The Assembly sequence will form the basis of the decision methodology about automation. In fact, the product assembly sequence will be analyzed in order to treat each task of the whole assembly in a specific technology that may be manual, automatic, or robotic. This should make possible the assembly to be a full manual, a full automated, a full robotic, or a hybrid system with combinations of these systems as elementary modules or subsystems. The optimization methodology should fix all the tasks of the assembly in a technology according to the methodology decision criteria. In order to achieve this, a graphical methodology should be built allowing the representation of the assembly sequence basing on standardized elementary motions. And that what will be defined in the next chapter.

3.2.3. Position with regard to Quality level required

The product quality level required may impose or contribute in the LoA of the assembly system. In fact, the quality required may force or impose some operations in a specific process technology or prohibit some tasks in a technology considered not suitable for them. For example, generally, for a reproducible quality an automated or robotic system is suggested. Manual assembly may not ensure such quality and don't allow a high level of accuracy. In another way, manual assembly may be preferred for some complex assembly operations that are too difficult or costly to automate and allowing an equivalent or satisfactory quality or sometimes even better.

3.2.4. Position with regard to Ergonomics

Similarly, the ergonomics criterion may impose or force tasks from the assembly sequence in a specific technology. In fact, for ergonomic sake, some tasks or motions are not allowed to execute manually for internal rules, national ergonomic rules, or international standards.

3.2.5. Position with regard to Manufacturer Strategy

The decision about automation is considered as an important decision especially considering the fact that it suggests a high investment and that it influences the product quality. This decision should be aligned with the manufacturer strategy [15]. That's why an effective decision about automation should be validated and ideally collaborated with the manufacturer strategic deciders [49][50].

It was noted that successful decisions about automation go in line with what the company aims for in the long term and the decisions are synchronized with the manufacturing strategy [48]. It was also pointed out that without linkage to the manufacturing capabilities, such investments may become real failures [23].

In the proposed decision methodology, the manufacturer strategy criterion or agent can allow or forbid some choices in the assembly system. This factor is able to prohibit manual execution for some tasks and even all the tasks, and same for automatic and robotic execution.

3.2.6. Position with regard to manufacturer economic situation and ability

The process level of automation should lead to an approachable, purchasable and manageable system for the company in the simplest way. That's why the process cost should be convenient to the manufacturer capabilities from the economic perspective. For example a solution respecting all the criteria and leading to a least costly product unit considering the production during all the period of the product market life, but demanding a high initial investment or excessively costly equipment at the launching phase that cannot be purchasable for the manufacturer, should be canceled and a second solution of automation should be found, even if it will lead to a more expensive product unit than the first solution, because this may be realizable for the manufacturer even if it is less profitable. So the automation solution, in order to be valid, should check the feasibility from economic point of view, and the initial investment should be accepted by the manufacturer and inferior to a maximum investment threshold. And this should be managed in the decision methodology.

3.2.7. Position with regard to social aspect

The social aspect should be considered when deciding about automation. This decision should respect the culture within the manufacturer and the personnel who may be impacted by the decision. Opting for a full automated or a full robotized process may lead to lay off workers, and this solution is generally not convenient and avoided for the manufacturer because many problems may result from such decisions, and in some cases the manufacturer don't have the possibility to do it. From another point of view, when opting for a process technology, the manufacturer should be sure to find available competences that is able to ensure the required tasks, whether for manual execution, or for automated and robotic manufacturing which demands extra tasks such as maintenance, and specific skills for using manufacturing systems generally highly computerized, reconfiguring machines, or reprogramming robots. According to the social aspect, some tasks may be forbidden in automated or robotic. The social aspect may also prohibit manual if for example there is a lack of competent workers to execute manual tasks in a required quality level, leading to automate or use robots in the corresponding tasks.

3.2.8. Position with regard to Local laws

According to the plant location, the manufacturer is subject to the local laws and should respect related engagements. Some of these laws impact the decision about automation. For example in some countries like China the manufacturer is engaged to recruit a defined minimum number of employees according to its size. This should be taken into account when deciding about automation in order to not design a system requiring an inferior number of labors and being obliged to violate laws or having under load because of exorbitant number of worker comparing to that one the system requires.

3.3. Industrialization Information involved in the decision

The decision methodology about automation should involve the maximum possible of the industrialization information available. The information to consider concerns the planned production criteria and estimations about the future manufacturing. The most information to consider the more accurate the decision will be, supposing that these information and estimated manufacturing criteria are seriously developed and are the nearest possible to the future production reality. The information may concern: the volume planned, the market life of the product, the product rate required or the cycle time, the down time rate, the maximum rejects allowable, the space available for the manufacturing and the monthly cost per square meter...

3.4. The decision making methodology and the solution justification

The decision methodology should take into account all the criteria cited above and should ensure an assembly system that respect all the requirement and the capabilities with forcing assembly tasks in manual, automatic, or robotic if the requirements leads to. In the optimization, the methodology will consider tasks where the choice is not forced and where there is a free choice to select the technology indifferently and without specific requirement. The first step is to calculate the product unitary cost considering all these indifferent tasks by default in manual. Then, in each iteration automate block by block and calculate the cost and this represents an automation solution. At the end the solution to keep is the one presenting the minimum cost, and consequently and obviously respects all the requirements and factors respected before.

The industrialization information will be exploited in the methodology in order to calculate the product manufacturing cost for each solution and in justifying automatic or robotic investment. In fact whatever are the requirements and the issue, the capital investment in automatic machinery must be amortized over the market life of the product [95], and automation will be difficult to justify if the market life of the product is short [95], this issue should be anticipated and argued before doing the investment, and the economic justification of the solution should be present and demonstrated.

3.5. Outline building for the decision about automation methodology

We represent the following state chart of the methodology explaining graphically and globally the decision methodology or algorithm (figure 6). In this figure the green color represents the standards to develop for the calculation as static constants or data base of standard values of time estimation for all motions and for all the characteristics that affects time estimations and the corresponding timings. The blue colors consists on the decision algorithm global actions, and the mauve color represents its inputs colored with graduate color representing the degree of possibility to change or negotiate these inputs where the least dark represents the least difficult to be changed or adapted.

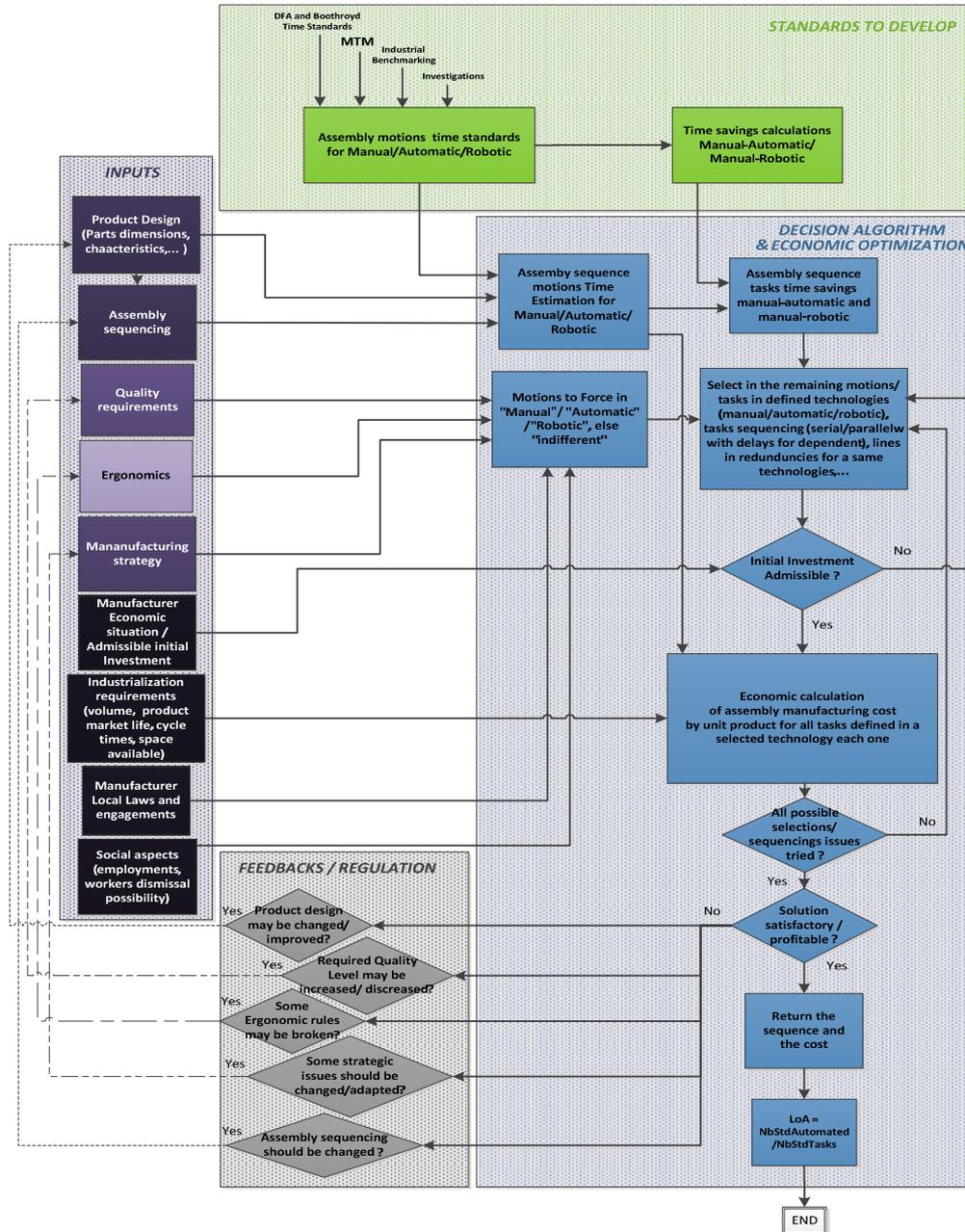


Figure 6: The Decision about Automation Methodology outline

3.6. Conclusion

In this chapter the position of the decision about automation in the manufacturing procedure was defined and the information concerning the assembly manufacturing that may be known at an early stage generally defined by managers, industrialization and marketing team within industries. The decision outline was also defined with the presentation of state chart showing the involved information and the global decision algorithm and tools showing the possible interaction and changes, and the need to an economic model for cost and profitability evaluation of the solutions, and to an assembly sequence representation method in order to facilitate the assembly representation and sequencing in order to allow the decision and make it possible and clear. This is what will be the aim of the next chapter during which a literature review of the assembly representation methods will be presented leading to a new assembly modeling language in order to fulfill the requirements that may not be fulfilled by the existent methods.

CHAPTER 4. A new modeling language building for assembly sequences representation and optimization: The Assembly Sequences Modeling Language (ASML)

4.1. Introduction

The decision methodology, as shown in the previous chapter, needs a graphical modeling language for representing the assembly sequence clearly and accurately. This will contribute to determining the assembly tasks that may be automated or executed manually according to the factors and criteria to consider in the decision methodology. These criteria, may force as shown previously (figure 6) some tasks in manual, automatic, or robotic execution. Other tasks, being not forced and consequently considered in “undefined” state or technology, will be decided in the cost optimization procedure using a cost model calculating the product cost for every possible solution. This economic model will involve industrialization information concerning the designed product and the planned production information which should be available at an early stage before the assembly system design. The graphical tool that will be defined during this chapter should allow understanding, defining and deciding LoA of tasks in the convenient technology and should be a standardized tool for representing assembly sequences and processes, whatever is the technology used or to use for every task in assembly. This should make possible the assembly to be a full manual, a full automated, a full robotic, or hybrid system with combinations of these systems as elementary modules or subsystems. One of the most important goals and purposes with the assembly tool is optimizing the assembly sequence from timing point of view by representing possible parallelism between independent tasks in the product assembly sequence leading to reducing the assembly timing and consequently the cost. The methodology definition during this chapter will start by the requirements definition that the tool should meet. Then presenting the existent graphical methods already used in assembly. A next section will present the existent representation graphical methods that may be exploited in building the graphical tool according to the presented requirements. Then the graphical tool representation and definition will take place. The chapter will end by a representation of assembly sequence using the tool for an example of assembly manufacturing.

4.2. The assembly modeling language’s requirements

The modeling language will be designed in order to fill defined requirements that are conceived in order to help in the decision methodology and the decision algorithm building further. This modeling language will represent a platform on which the decision will be based. That’s why it should be well designed in order to be as accurate and representative as possible. It should be enough clear and should provide a good visibility about the assembly sequence for every assembly process whatever are the product, the context, and the technology to use.

The requirements that the desired assembly modeling language should fulfill are as follows:

- Requirement 1: A Graphical representation

For a better visibility, the assembly modeling language should be designed as a graphical representation language.

- Requirement 2: A sequential representation

The modeling language should show clearly the sequential aspect of the assembly sequence with the precedence aspect between the serial tasks in the assembly sequence.

- Requirement 3: Transitions between the assembly tasks

The transition allowing passing from an assembly task i to its successor j should be shown in the assembly representation language to design.

- Requirement 4: Decisions and choices

In assembly it may be possible to have a choice between assembly procedures according to a defined previous condition or transition. In fact a condition may make the choice in the executions between a sub-sequence A or a sub-sequence B . the modeling language should make possible doing this.

- Requirement 5: Representing parallelism for independent tasks

When some tasks are completely independent and no precedence conditions between these tasks exist, the modeling language should make possible to show this graphically.

- Requirement 6: Representing parallelism for dependent tasks

When dependence between parallel tasks exists in the whole of the assembly sequence imposed by a precedence constraint, this should be managed and represented using the assembly representation language. This management may be ensured by making lags or delays between dependent tasks in parallel sequences.

- Requirement 7: Representing material flows and needed resources for task execution

The needed tools and components for each task in the assembly sequence should appear in the representation using the modeling language. In fact, the needed tools for all the assembly sequence should be known before starting the execution of the assembly when considering the needed tools for all the tasks.

- Requirement 8: Representing the final product assembly nomenclature

After representing the different serial and parallel tasks leading to sub assemblies' constitution, the final product assembly should be visible by assembling the sub products with referencing to the assembly sequences of each sub product as by managing by unique key or procedure name for each sub assembly.

If the final product assembly is simple from number of assembly tasks point of view, it should be possible to represent directly the assembly sequence leading to the final product without making sub assemblies and procedures.

- Requirement 9: A standard representation independent from product type or context

The graphical modeling language should allow by a same manner and simply the representation of assembly sequences whatever is the product type. This representation should be unique and every person who uses this modeling language should provide a same representation for a given assembly sequence to represent. To do this, a vocabulary of assembly motions will be defined and the assembly representation should use only these motions or assembly verbs which should be standardized and exhaustive in order to allow the representation of all possible manufacturing operations in assembly.

The assembly sequences representation language should fulfill all these requirements and exigencies. To build this modeling language, the existent modeling languages in the domain will be consulted. And as some existent modeling languages respond to some requirement; these modeling languages will be exploited and combined in order to participate in the method building satisfying all the requirements and criteria.

4.3. The existent modeling languages useful in assembly sequences representation

4.3.1. A literature review about existent modeling languages

In the industrial assembly representation domain, many modeling languages and methods were found. Some of them concerns the product hierarchy from which assembly sequences may be directly deductible, and others are dedicated to represent only the assembly sequence.

A literature review was established about the modeling languages used in assembly and others used in other fields which seem to be useful consisting on the Sequential Function Chart (SFC) method and Gantt method in order to search if a method exists in the literature fulfilling the defined requirements. The modeling languages found were evaluated from some usefulness perspectives consisting on how the assembly sequence is deduced from the representation, the possibility of using a referencing system for sub-assemblies (table 4).

In fact determining the assembly sequence from the representation is not always obvious and requires an effort for deducing an adequate assembly sequence, because the majority of the existent tools used in assembly are build to represent the product as a first aim, its architecture, and how the parts are organized and the relations between them (table 4). The assembly sequences are deductible from these representations and generally the representation allow to deduce all the possible assembly sequences, and this is the case of all the found methods used in assembly excepts the Connection Semantics Based Assembly Tree (CSBAT) method and the liaison diagram method (table 4).

The second important factor that should be present in the modeling tool to build is the possibility of using a referencing system in representing the assembly sequence leading to the final product assembly. This system, inspired from computing principles and the use of procedures, allows referencing sub-assemblies in a graph assembly in order to define its assembly sequence independently for many issues: simplifying the graph, increasing reusability, limiting redundancy, avoiding risk of error allowing changing the assembly in only one graph if there is a change to do instead of doing the change everywhere the sequence exists. We present the existent modeling tools used in assembly in the table 4, we evaluate them by the factors cited, and we present a graphic example from the literature and a citation where the corresponding method is explained in details.

Table 4: Literature review in modeling languages useful for Assembly sequences representation

Existent modeling languages used in Assembly Representation						
Purpose / Domain	Representation		Assembly sequence deduction	Possibility of using procedures/ referencing	The method's graphic structure by an example	Use/Description in the literature
	Node	Arc				
Product design hierarchy representation	Scenegraph					
	Parts, sub-assemblies, final product	Relations between parts	Indirectly: effort of interpreting the graph to build assembly sequence	Possible	Figure 26 Appendix	[106][107]
	Hierarchical Structure Model					
	Parts, sub-assemblies, final product	Relations between parts	Indirectly: effort of interpreting the graph to build assembly sequence	Possible	Figure 27 Appendix Figure 28 Appendix	[108][109]
	Hierarchical Relation Graph					
	Parts, sub-assemblies, final product	Relations between parts	Indirectly: effort of interpreting the graph to build assembly sequence	Possible	Figure 29 Appendix	[109]
Product design parts relations types representation	Relational Model					
	- Part entities in rectangles - Contact entities in circles - Attachment entities in triangles	Relations between parts	Indirectly: effort of interpreting the graph to build assembly sequence	Not Possible	Figure 31 Appendix	[113]
	Graph of Connections					
	Parts to assemble	Relations between parts	Indirectly: effort of interpreting the graph to build assembly sequence	Not Possible	Figure 32 Appendix	[113]
	Connection Semantics Based Assembly Relational Model (CSBARM)					
-Parts to assemble in rectangles -Connectors in the Assembly(screws..) in ellipses	Relations parts-parts, connectors-parts	Indirectly: effort of interpreting the graph to build assembly sequence	Not Possible	Figure 33 Appendix	[108]	
Assembly all possible sequences representation	Precedence Graph					
	Parts to assemble	Order of adding parts/ choice for arcs exiting a same node	Indirectly: the graph gives all possible sequences	Possible	Figure 34 Appendix Figure 35 Appendix	[95][109]

	AND/OR Graph						
	Parts, sub-assemblies, final product	Parts composing sub-assemblies/ final product	Indirectly: the graph gives all possible sequences	Possible	Figure 36 Appendix Figure 37 Appendix	[112][113]	
	Parts Tree						
	Parts, sub-assemblies, final product	Decomposition or composition of sub-assemblies, final product	Indirectly: the graph gives all possible sequences	Possible	Figure 38 Appendix	[111]	
Assembly specific sequence representation with limited flexibility of sequencing	Connection Semantics Based Assembly Tree (CSBAT)						
	Parts	Order to adding the part to the assembled sub-product or final product	Directly: the parts to add to the assembly are fixed but the order of assembling the sub assemblies is not fixed: no rigid sequencing	Possible	Figure 39 Appendix	[108]	
Assembly specific sequence representation	Liaison Diagram						
	Parts	Relations between parts	Directly: the graph gives all the possible sequences but following the numbered arcs it leads to a unique sequence	Not Possible	Figure 40 Appendix	[111]	
Modeling languages used in other fields but may be exploited for Assembly Representation							
<i>Purpose / Domain</i>	<i>Representation</i>			<i>Sequence deduction</i>	<i>Possibility of using procedures/ referencing</i>	<i>The method's graphic structure by an example</i>	<i>Use/description in the literature</i>
	<i>Step</i>	<i>Transition</i>	<i>Arrow</i>				
Programming PLCs (programmable logic controllers) and preparation for systems control	Sequential Function Chart (SFC)						
	Actions	Conditions	Link step-transition	Directly: Only one definite sequence is represented	Possible	Figure 41 Appendix Figure 42 Appendix	[114][115]
<i>Purpose / Domain</i>	<i>Representation</i>			<i>Sequence deduction</i>	<i>Possibility of using procedures/ referencing</i>	<i>The method's graphic structure by an example</i>	<i>Use/description in the literature</i>
	<i>Rectangle</i>	<i>Arrow</i>					
Project Schedule	Gantt						
	Tasks	Precedence constraints between tasks	Directly: a specific and accurate sequencing is represented	Not Possible	Figure 43 Appendix	[116]	

4.3.2. Discussion about the compatibility of the presented modeling languages and the defined requirements

After presenting the existent modeling tools that may be used in assembly, we discuss in this section the compatibility with what we require in the decision methodology and what we require from the modeling tool in order to be useful. In order to achieve this, we look for every method encountered in the literature the fulfillment of the requirements that we defined in the section 4.2.

We use a method of evaluation inspired from [120] and we present the result of compatibility methods-requirements in the table 5 representing a matrix populated in a manner indicating the row element consisting on a modeling language strongly fulfill (filled circles), weakly fulfill (unfilled circles), or don't fulfill (empty) the requirement in the corresponding column element.

Table 5: Existent modeling languages and requirements fulfillment

	<i>The Requirements</i>								
	<i>Req 1</i>	<i>Req 2</i>	<i>Req 3</i>	<i>Req 4</i>	<i>Req 5</i>	<i>Req 6</i>	<i>Req 7</i>	<i>Req 8</i>	<i>Req 9</i>
<i>Scenegraph</i>	●			○	○			●	○
<i>Hierarchical structure model</i>	●			○	○			●	○
<i>Hierarchical relation graph</i>	●			○	○			●	○
<i>Relational model</i>	●			○	○			○	○
<i>Graph of connections</i>	●			○	○			○	○
<i>CSBARM</i>	●			○	○			○	○
<i>Precedence graph</i>	●	●	○	○	●			●	●
<i>AND/OR graph</i>	●	○		○	○			●	●
<i>Parts tree</i>	●	○		○	○			●	○
<i>CSBAT</i>	●	●		○	○			●	○
<i>Liaison diagram</i>	●	●						○	○
<i>SFC</i>	●	●	●	●	●	○	○		○
<i>Gantt</i>	●	●			●	●			○

It can be seen in the table 5 that no existent modeling language from the studied fulfills all the requirements that we defined in the section 4.2, and this justifies the need to build a new modeling language dedicated to assembly. However, there are some methods that are not so far from what we require.

The Sequential Function Chart (SFC) method is the nearest modeling language from what we require from a method allowing representing the assembly sequence in order to analyze and optimize it for the issue of deciding about the level of automation in assembly. This method fulfills perfectly the requirements 1 to 5 but fulfills partially the requirements 6, 7, and 9 and don't fulfill the requirement.

In fact the requirement 7 is not fulfilled by any existent method because it is a specificity of the task of optimization of our topic. The requirement 6 is also no fulfilled except by the Gantt method specialized in tasks sequencing managing the dependent tasks in parallel execution by making lags and delays making a task B waiting for its predecessor A if a precedence constraint exists between task A and B. It is consequently worthwhile to consider this principle in the method building because it represents one of the goals of the specific problem of optimization.

The requirements from 2 to 7 are not generally fulfilled by the graphical methods used in assembly. This may be explained by the fact that the existent methods for assembly are dedicated to product nomenclature and representation for assembly and not assembly sequence representation.

The SFC and Gantt principles will be considered and combined. These methods when combined are fulfilling the requirements defined except requirement 7, 8, and 9 that should be also satisfied. For the requirement 8, it was fulfilled by other methods such as the precedence graphs as shown in the table 5 because of the applicability of the referencing principle and noting sub-assemblies by labels (figure 35 Appendix) and defining them independently in another graph, this principle advantages were noted and explained in the section 4.3.1.

To fulfill the requirement 7, the method to design should manage this with an inspiration from SFC the only one fulfilling partially this requirement. The modeling language has to make a structure where we define the needed tools in the transitions conditions.

For the requirement 9, and in order to make a representation unique at least for a given assembly sequencing, a vocabulary should be defined for the modeling tool describing the verbs and actions to use for assembly motions. So a standard list of assembly motions should be defined, and this is what will be done in the section 4.4.3 in this chapter.

4.4. The modeling language definition and building

4.4.1. The modeling language's definition and basis

The designed modeling language is dedicated to represent assembly sequences basing on tasks representation and not product design hierarchy. The modeling language should present the tasks to execute in assembly in order to accomplish the product assembly from the beginning to the final step leading to on the assembled product. The assembly sequences representation modeling language should meet all the requirements defined in section 4.2 and should allow the representation of assembly tasks sequencing in order to help in the optimization of the assembly sequencing when optimizing in the cost using the economic model to design. In fact, the assembly sequencing impacts directly the product cost and the need to more or less workers, machines, or robots when envisaging. For example, executing independent tasks in parallel requires more workers in manual, more machines in automated, and more robots in robotic. This impact the product cost by increasing or decreasing the final product cost when considering all the involved information in the economic model calculation. The modeling language should allow figuring the execution of tasks in serial or in parallel, the tasks sequencing and the eventual dependency for tasks in parallel subsequences needing foreseeing lags as described in the requirement 6 in section 4.2. The methodology should also verify obviously all the other defined requirements in that same section. The modeling language will have as basis some principles used in SFC and Gantt methods.

4.4.2. The modeling language's basic structure and symbols

Basically, the modeling language is a transition graph consisting on steps (figure 7.a) and transitions (figure 7.b) representing assembly motions and tasks.



Figure 7: Steps and transitions symbols

Then initial steps for the graphic modeling language are designed as shown in the figure 8.



Figure 8: The initial step symbol

Each step contains one and only one action (figure 9) consisting on an assembly elementary motion that can be executed manually, can be automated, and can be robotized.

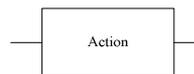


Figure 9: Actions within Steps

Each transition contains the conditions allowing transiting from a task i to a task $i+1$ (figure 10). We make difference for these conditions between conditions that we label C_x representing the end of the execution or result of the action i that reflects generally the need to an indicator in manual execution or to sensors in automated and robotic execution, and C_y representing the tools and parts needed to the execution of the motion $i+1$. Considering all C_y of the graph, the needed tools to assemble the product and the product parts can be determined basing on the assembly representation using this method by summing on these conditions C_y .

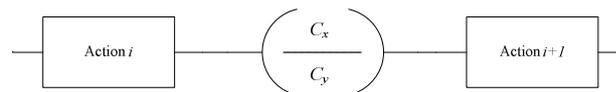


Figure 10: Conditions within transitions

Two steps should not be directly consecutive (figure 11).

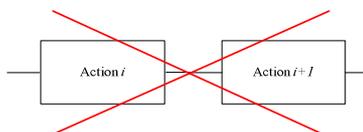


Figure 11: Forbidden directly consecutive steps

Two transitions should not be directly consecutive (figure 12).

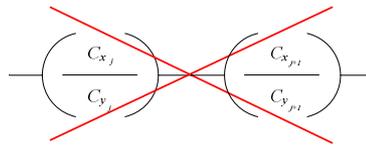


Figure 12: Forbidden directly consecutive steps

We define the Action “Wait” consisting on the wait to a validation of a condition when nothing is to be done. This fictive action allows also the respect of the structure and rules of the language. This fictive action may be used when needed or when being in a situation of abusing rules (example figure 34)

The representation of an assembly sequence using this modeling language may have more than one initial step. In fact when tasks are designed to be executed in parallel, this requires another starting point of another sub-sequence (figure 13).

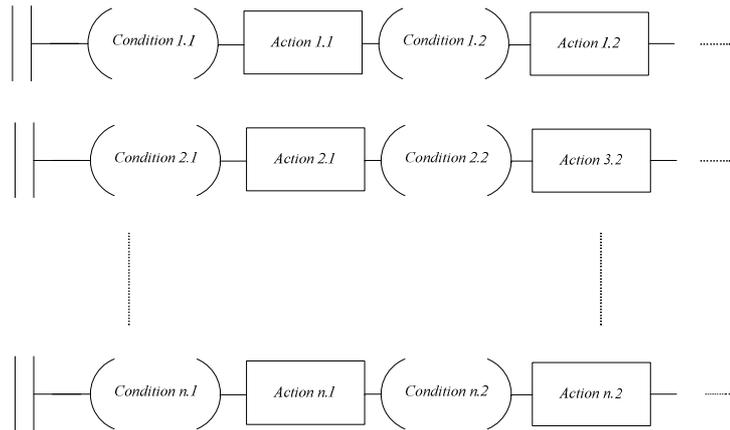


Figure 13: Multiple starting points in the graphic modeling language

The Transitions in AND/OR divergence and convergence are possible in the designed modeling language, the figure 14 shows the basic transitions types in the designed graphic modeling language where (a) shows AND divergence, (b) the OR divergence (c) the AND convergence, and (d) the OR convergence.

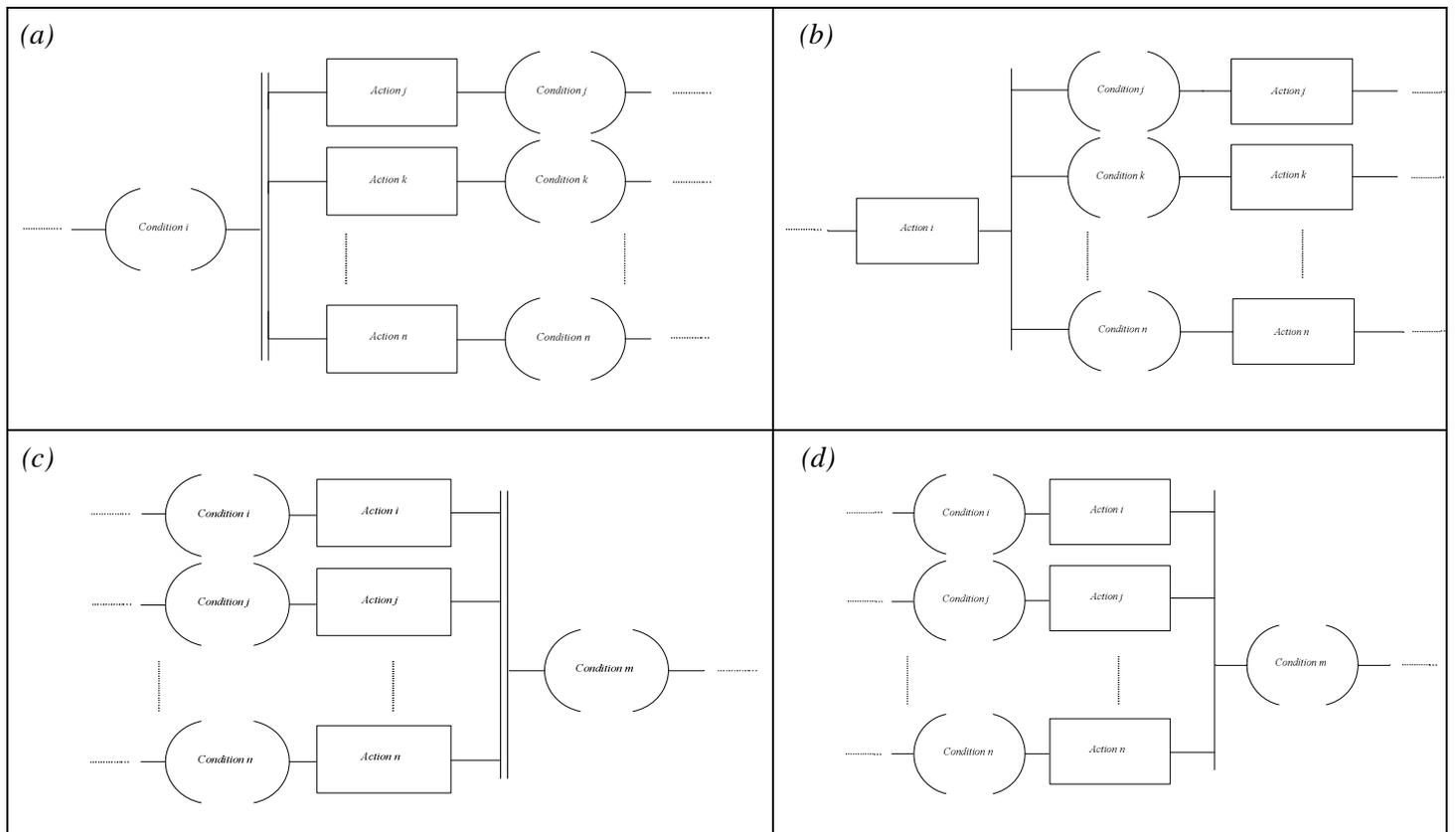


Figure 14: AND/OR divergence and convergence symbols

The end of assembly leads to the final product. This end of assembly is represented by the double circle (figure 15).

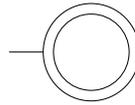


Figure 15: The end of assembly symbol consisting on the final product assembly accomplishment

The figure 16 shows a complete simplified assembly sequence representation leading to the final product.

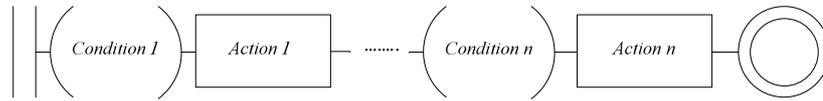


Figure 16: A complete assembly product sequencing representation using the modeling language

If the product is complex or contains numerous parts, this may be managed by the modeling language using procedure or sub-products whose symbol is shown in figure 17.

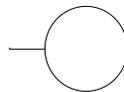


Figure 17: The sub-product symbol

We define the action “Wait” consisting on a fictive action or a fictive step without an effective task to execute. This fictive action has many purposes and may be used in many situations. It allows the respect of the modeling language rules when falling in a case leading to a non respect of these rules, it may be intercalated between the 2 conditions (in figure 12) as when needed to show some conditions separately in the representation.

The “Wait” action may also show a real wait of the validation of the previous condition, actions, or availability of sub-assemblies as shown in figure 18. It can be used after an AND divergence when additional specific conditions for the execution of each subsequence exist besides the entrance condition of this AND divergence. The figure 33 shows a simplified representation of this case where for sub-sequence y specific condition y is needed besides condition x and for the execution of sub-sequence z specific condition z is needed besides the condition entrance x.

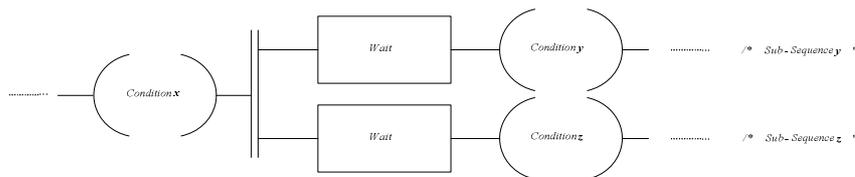


Figure 18: the 'Wait' instruction as a fictive step for managing specific conditions in an AND divergence

The “Wait” action can be used in order to show a “nothing to do” of a condition is verified. The figure 19 shows this case in an example of an OR divergence where when a condition X is verified some assembly tasks have to be executed, and when a condition Y is verified generally including the complementary of X consisting on \bar{X} , there is nothing to execute in assembly.

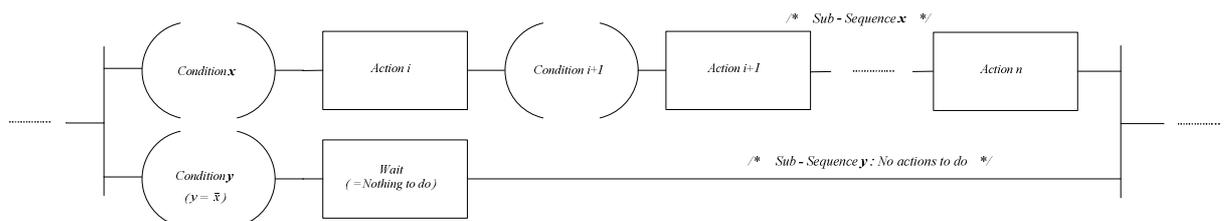


Figure 19: The 'Wait' instruction as a 'Nothing to do' step according to the conditions in an OR divergence

The designed modeling language offers consequently the possibility to represent assembly sub-sequences leading to sub-products (figure 20). These sub products references that can be written within the symbol circle shown in figure 20 may refer in other graph to the sequence corresponding to that sub product. This use remembers the computing principle and the referencing and procedures. To refer to this sub product assembly it will be sufficient to design the circle with the reference of that desired sub product within as a procedure of assembly in other graphs or on the final product assembly graph. This may simplify the design of the assembly sequences using this graphic modeling language.

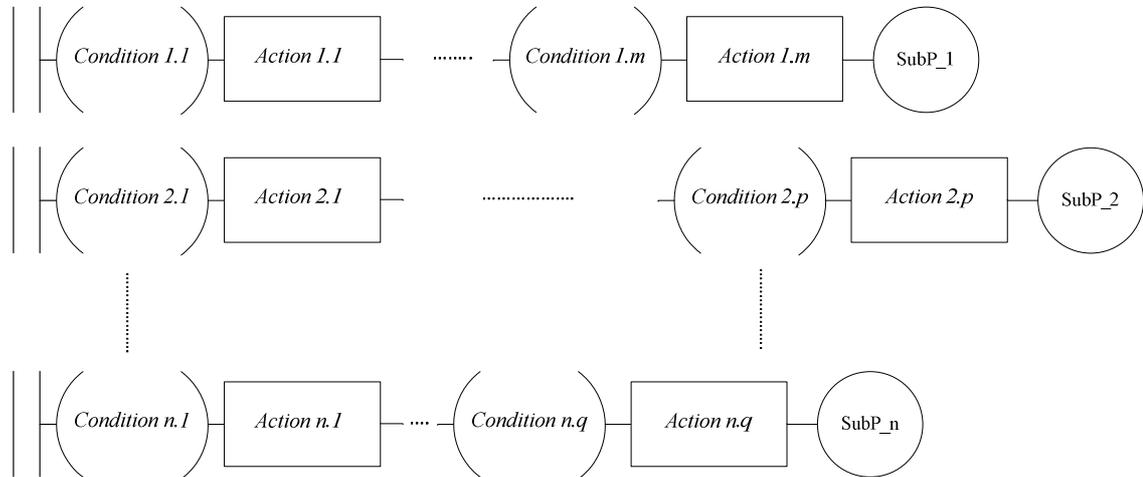


Figure 20: Assembly of sub-products

After a representation using sub-products, the way to represent the final product remains possible using directly labels of sub-product in a graph leading to the final product (figure 21).

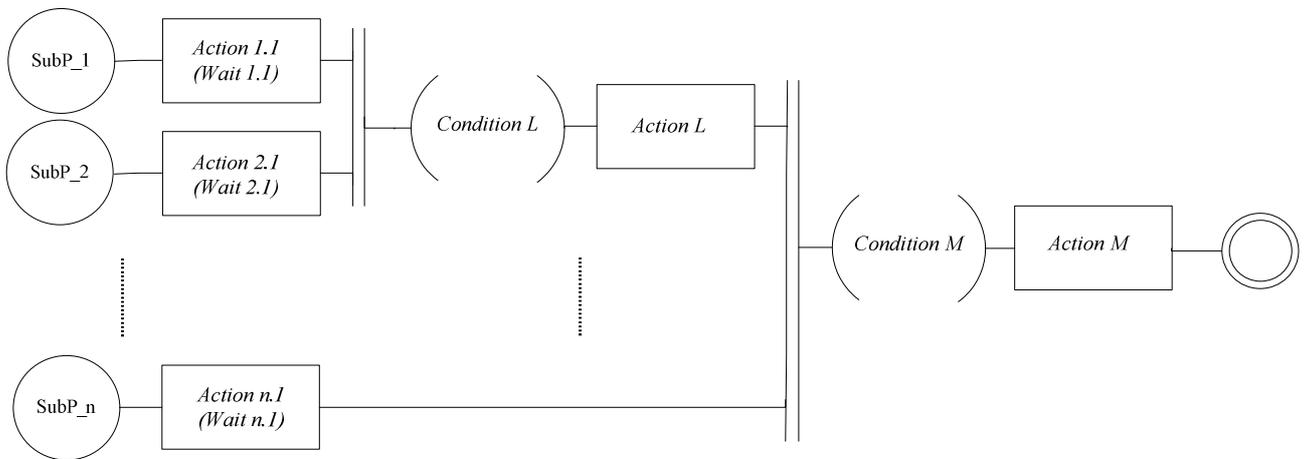


Figure 21: Assembly final product representation using referencing of sub-products assembly

When dependencies between tasks in parallel sub-sequences exist, this should be managed by the modeling language by making a lag following the Gantt principle. When a precedence constraint between a task x and a task y exists causing this lag, this should be shown using this modeling language by an arrow from x to y .

The figure 22 shows in (a) a lag between the first subsequence and the second subsequence that may be caused by precedence constraint between the $Action 1.n$ and the $Action 2.1$. In the figure 22 (b) two lags exist: the first show the precedence between the sub sequence 1 ending by the $Action 1.n$ and the sub sequence 2 starting by the $Action 2.1$, and the second between the $Action n$ and the subsequence starting by the $Action 3.1$.

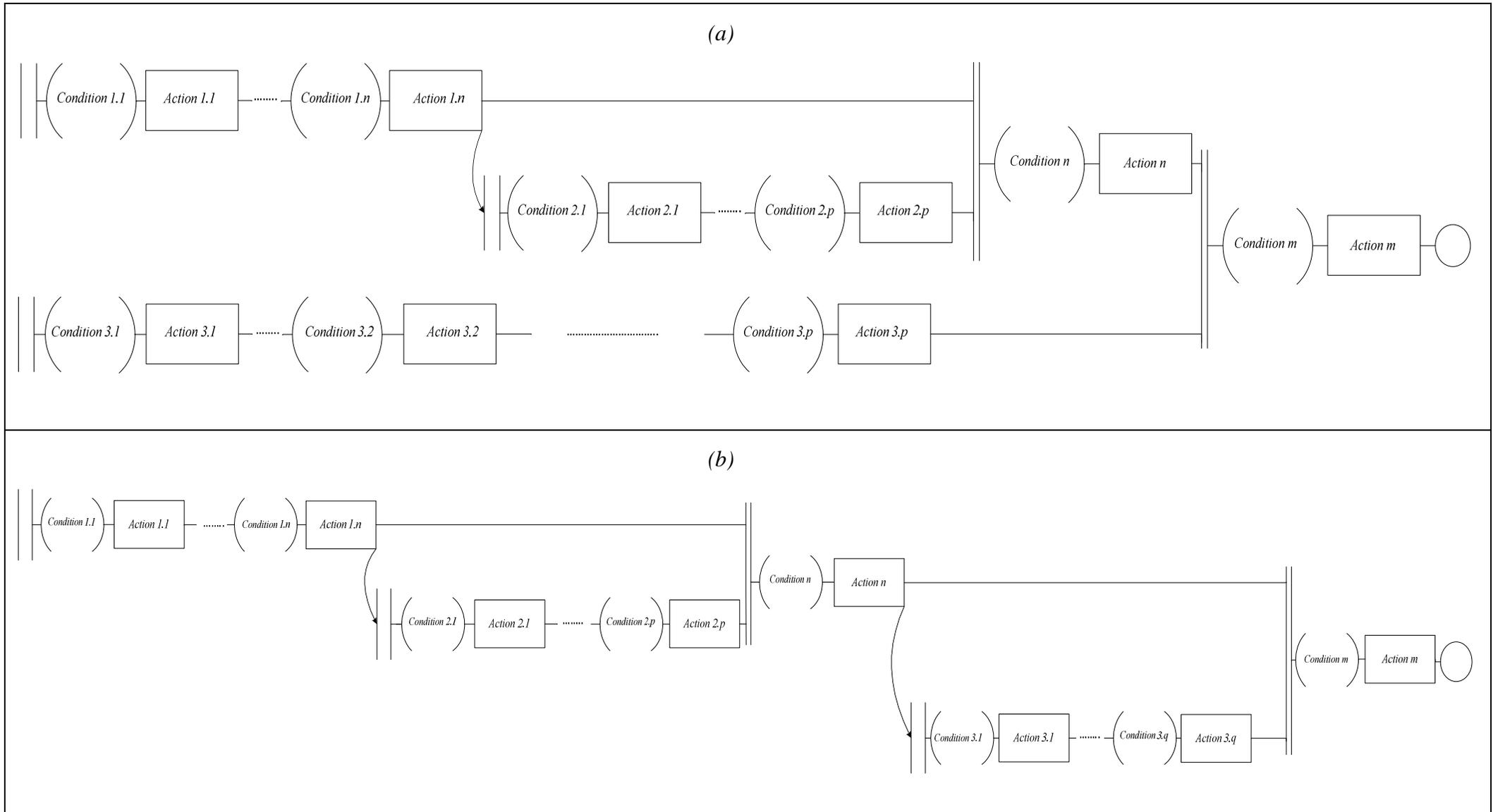


Figure 22: Dependent tasks in parallel sequences and management by delays

If the sequencing is designed representing perfect parallel tasks without lags, this reflects that one or more than an additional worker or machine is needed. This affects the product cost. This ability of representing sequencing and lags demonstrates one of the most important contributions of this modeling language leading to how optimizing the cost from assembly sequencing issue, aided by the conditions before and after these tasks of sequences to be executed in manual, automated or robotic technologies informing about the complexity to accomplish this in a technology or the other.

In order to allow estimating and optimizing easily, efficiently, and similarly for every assembly sequence whatever the product and the domain is, and in order to make automating this decision and building a computerized decision support tool further, it may be useful to define a standard vocabulary for the graph, and especially for the time costing elements in the graph: the assembly motions. And this is what the aim of the next section will be about.

4.4.3. The modeling language's assembly motions and vocabulary standardization

The aim of the graphical modeling language is to contribute efficiently in the decision making, to make the decision easier and to help in the optimization of the assembly system to design.

The assembly time impacts the cost when considering for example the product labor cost calculated by multiplying the workers labor rate by the time required for the product.

The assembly sequencing architecture impacts also the product cost basing on the graphic representation language defined. In fact, when for example two perfect parallel sequences without lag exists, this requires more resources in workers if these tasks are executed in manual, of machines if automated, and of robots if robotized. These impacts obviously the product cost from labor cost in manual because the increased number of workers, the machines cost like the investment because the increased number of machines is increased, and the robots costs because the increased number of robots.

Using this graphic modeling language many parameters impacting the cost are directly visible or determinable like the cited parameters such as assembly sequence architecture and assembly time, but also others such as the tools needed or machine tools that can be found in the transition conditions C_y like it was described in the modeling language definition in section 4.3.2. These tools and machines determination in order to calculate their cost in the product may be done basing on the modeling language. Also needed sensors, indicators, or control architecture for automatic or robotic assembly may be discussed by designers using condition C_x and also the assembly tasks sequencing.

In order to make this contribution the most objective, organized, easy as possible and programmable in computerized evaluation or decision tool, the graphic modeling language vocabulary should be standard. This will be helpful in the assembly time estimation when we need to estimate the assembly time. The assembly time comes from the time costing elements in the assembly sequence consisting on the assembly motions. That's why we have to standardize the assembly motions and estimate the required time for each motion. The standardized motions are shown in table 6 based on studies done in Cedar laboratory in Clemson University where the vocabulary was built and studied [117][118][119] to which we add the motion 'Identify' as shown in the table 6.

The previously defined fictive action or modeling language specific instruction named "Wait" is not considered as time costing when considered alone because nothing is to be done for this motion and the assembly time estimation for the sequence is evaluated to the minimum and supposed to be in al lean manufacture and where there is no time waste. This fictive action is consequently theoretically evaluated to duration of zero seconds.

The motions time estimation will be studied in the next chapter. These verbs are convenient to describe manual, automatic or robotic assembly execution (table 6).

Table 6: The standardized Assembly Motions

Standardized Verbs list			
S. No	Verb	Definition	Example
1	Align	Accurate Positioning of a part or tool over another part	Align bumper to BIW
2	Apply	Putting on a medium on an object with or without the aid of a tool	Lubricate headlight seal initial
3	Attach	Setting or binding two parts with each other using only the features on each part	Attach hook to ARB
4	Clean	Includes all performances, to clean an object with a tool.	Clean windshield with wipe
5	Connect	Includes all activities to connect/ locking or unlocking a cable, with or without tool.	Connect cable to harness
6	Disengage	Unlocking a fixture or removing a part from the fixture or tool.	Disengage the fixture / Remove Jig
7	Engage	Locking a fixture or engaging a tool onto a part.	Engage a fixture or clamp.
8	Exchange	Involves exchanging empty bins containing parts and supplies with full bins.	Exchange container nuts
9	Get	Picking up a part or tool from around 1 m or does not necessitate getting up or walking from position.	Get torque tool
10	Handstart	Screwing in 2 rounds, the bolt or nut by hand or with the aid of tools, to set it in position.	Handstart first screw on tool holder at lift assist
11	Insert	Includes all activities to assemble clips with hands and/or tool	Insert clip to Y-strut
12	Inspect	Carrying out a check on a part or process, in order to make a decision.	Inspect bumper for damages
13	Lay	Laying a cable by hand and/or fastening exactly	Route Bowden cable
14	Move	Moving with/without a part/tool around the car or actions like bending down, squatting.	Move to front bumper
15	Open (Preparatory)	Includes all activities to handle packaging, separating layers and opening package to take contents.	Open bag with tool
16	Operate	Operating is to getting control over adjusting elements with a hand or foot and performing a single operation or a combined operation.	Operate to lower EMS onto hook

17	Place	Position a part or tool that is already in hand and requires no additional walking	Place ems hanger on third coil
18	Press (Switch/button)	Pushing a button or switching on a control to operate a tool.	Press button to release
19	Push	Manipulating a tool or part to align or start motion.	Push seat into place
20	Read	Reading information carrier, data cards to comprehend the information.	Read option list
21	Remove (Preparatory)	Includes all activities to handle packaging, separating layers and opening package to take contents.	Remove flex layer
22	Remove	Take a part off an assembly or piece of a part.	Remove a round cut out
23	Restock	Refilling storage containers, toolboxes and/or containers.	Restock rivets to carts
24	Restrict		Restrict cables.
25	Scan	Includes all activities to mark an object with a marking device or to document an object with a scanner.	Get scanner and scan label on IP skin
26	Screw in	Involves screwing in a bolt or nut completely with hand.	Screw in by hand total depth
27	Secure	Securing a cable with stationary or moveable fastening elements. With or without tools.	Secure cable for foglight
28	Snap	Clipping in parts with clips and onto other parts	Snap I-Panel Finisher into console stack
29	Tighten	Fastening screws and bolts with manual tools or torque tools.	Tighten 4 off screws with torque tool.
30	Unscrew	Unscrewing bolts/nuts manually or with help of a tool.	Unscrew adjuster 3 half turns 3mm gap
31	Walk	Walk from car body to car body or supply area without picking up part or any action. (and) Walk to supply area to pick up a part.	Walk to cart and back
32	Identify	Identify the right element to use from organized or mixed and disorganized package	Identify the wanted screw to use
33	Wait	Wait for a previous condition validation or for ASML rules respect	Wait for the availability of a needed part

4.5. Example of application

In Order to validate partially the modeling language built, a test on an example is worth doing. Therefore, we apply the language on a simple example.

The example consists in an assembly operation mode of a miniature simplified truck assembly which was observed during an assembly classroom training in the industrial engineering school GI-INP (figure 23). This course is taught for many ago to the industrial engineering students the assembly practically and providing knowledge about manufacturing techniques aiming to reduce waste and improve productivity such as lean manufacturing and 5S.

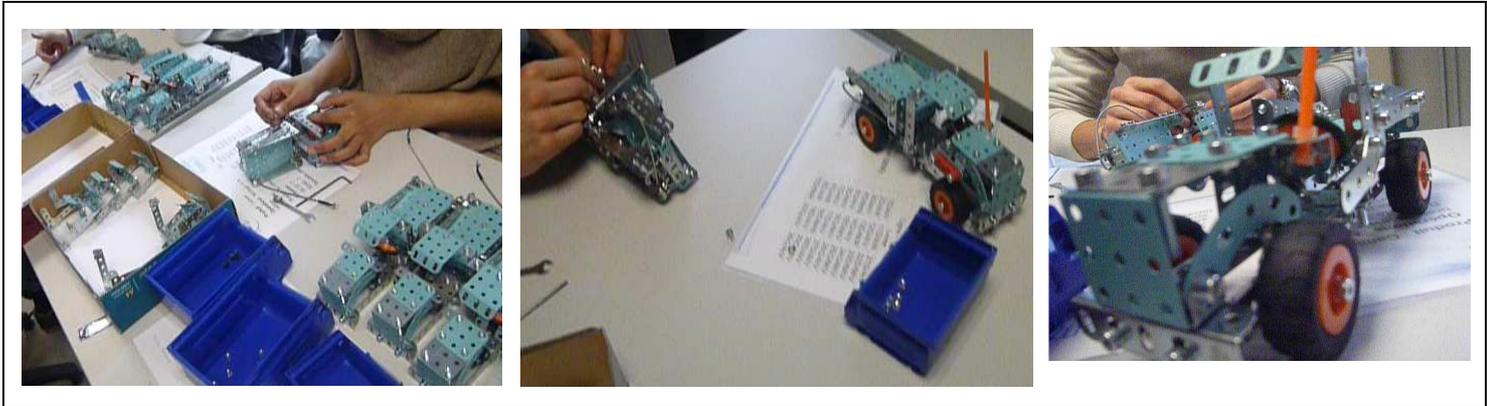


Figure 23: The truck assembly training

The assembly operation mode description is shown in the table 7. This operation mode is retrieved from the work instructions of the assembly training that the students should ensure during that course.

Table 7: The example assembly operating mode description

Step	Tasks
1	Pick a chassis randomly (left/right, manual/automatic)
2	Pick a correct dump truck (left/right) according to the chassis got (left/right)
3	Place the dump truck over the chassis on the back side
4	Handstart the group with a screw 6 and nuts in each side
5	Tighten using the key 7 and the Allen key
6	Place the chassis levers under the dump truck so that it matches with the last hole of the dump truck
7	Screw in the group with screws 20 and nuts
8	Tighten using key 7 and Allen Key
9	Restock the dump truck in the corresponding warehouse

We use the modeling language built with the standardized vocabulary in order to represent the described operating mode of the truck assembly sequencing.

The obtained representation is shown in the figure 24.

- **Interpretations**

The modeling language allowed the representation of the described operating mode.

The representation showed clearly the tasks and the conditions allowing the execution of these tasks. The material transition is also clearly shown in the transitions and this is useful for determining the needed tools and parts seeing this representation before starting the assembly.

The modeling language seems fulfilling all the requirements defined and allows all needed manipulations and information representation.

The representation may also be useful, in addition to the use further in the decision about automation, for the assembly workers especially novice. In fact the built representation method is usable to explain the assembly sequence that they will execute, thanks to the clearness and simplicity of the representation using the modeling language built.

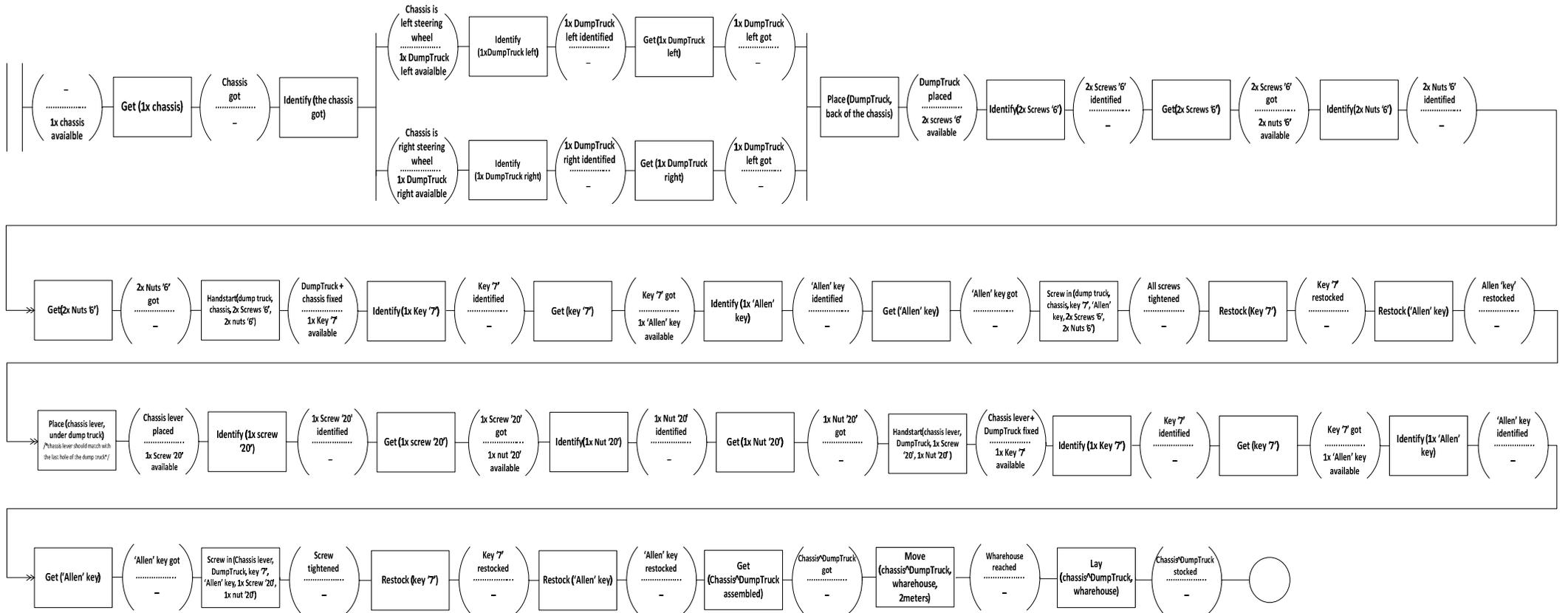


Figure 24: The Assembly Sequences Modeling Language (ASML) built applied on an assembly example

4.6. Conclusion

In this chapter, a new assembly modeling language labeled ASML was built and defined allowing a simple and clear assembly sequences representation and optimization from a sequencing point of view. This representation language was built after a definition of the needed requirements (section 4.2) that the assembly representation method should fulfill followed by a literature review proving the non fulfillment of these requirements by the existent assembly description methods.

The language built exploited some principles of the existent methods in order to fulfill the entire requirements. This led to the fulfillment of the requirements defined in section 4.2 consisting on the requirement 1 imposing that the method should be graphical, the sequential representation (requirement 2), the transitions between the assembly tasks (requirement 3), the decision and choices (requirement 4), the representation of parallelism for independent (requirement 5) and dependent (requirement 6) tasks, the representation of material flows (requirement 7), the representation of the final product assembly nomenclature (requirement 8).

In fact, all the requirements defined are fully fulfilled by the new modeling language built except the requirement 9 fulfilled partially (table 8). This requirement 9 about building a standard representation independent from product type or context is globally fulfilled considering the standard rules and vocabulary of the method defined, but when considering the uniqueness of the representation imposed also by the same requirement, this may be missing because the multiple possibilities of representation (serial, parallel, combinations,..). Moreover, this part of the requirement 9 is hard to verify. Yet, this requirement including the uniqueness may be fully fulfilled if we represent the simplest representation as all in serial, or the representation of the optimal sequence least time costing for example. Although we consider on the whole that the requirement 9 is partially fulfilled, but satisfactory fulfilled.

Table 8: *The requirements fulfillment by the Assembly Sequences Modeling Language (ASML) built*

<i>The Requirements</i>									
	<i>Req 1</i>	<i>Req 2</i>	<i>Req 3</i>	<i>Req 4</i>	<i>Req 5</i>	<i>Req 6</i>	<i>Req 7</i>	<i>Req 8</i>	<i>Req 9</i>
<i>The Assembly Sequences Modeling Language</i>	●	●	●	●	●	●	●	●	○

The built modeling language will be useful for the decision about automation because it will allow the representation and sequencing of the assembly sequence. This sequencing and the possibility of representation considering dependencies and delays will allow the evaluation of the assembly sequence duration estimation for a defined configuration if all the standard motions defined in the table 6 are estimated from timing point of view. When changing the sequencing by executing tasks in parallel for example will impact the assembly estimated duration, and also the needed resources requiring more resources to assume this parallel execution whether for manual assembly by duplicating workers, for automatic assembly by duplicating machines or lines, or for robotic assembly by duplicating robots allowing these tasks. This defines the need to estimate the assembly motions from timing point of view with a standard definition of times for the different technologies (manual, automatic, and robotic), and to set up a method to estimate the assembly sequence duration basing on the representation and on the motions estimated times. This is the purpose of the next chapter.

CHAPTER 5. Assembly sequence and motions time estimation, analysis, and time involvement in the decision about automation

5.1. Introduction

The assembly time, as shown in the figure 6, is involved in the decision about automation. In fact, the product assembly time impacts the assembly cost and consequently the product cost. In the designed modeling language ASML built in the previous chapter, the representation is proved able to represent the assembly sequencing and the assembly time duration. The assembly sequencing is important because it reflects directly the resources to use. When opting sequences in parallel, this requires more resources or duplicate resources. But when no resources available, it will be represented by a delay or lag between tasks and the task execution will wait the occupied resources liberation before starting. Therefore, this sequencing reflects the assembly investment and cost, and will be considered in the economic method to build in order to calculate the product assembly cost taking into account all the concerned parameters as the assembly time and the required workers, machines, or robots. It is consequently important to note that the sequencing taking more time is not evidently the least costly and the optimal one but it should be argued by the cost calculation using an economic model considering all the parameters involved as the resources cost required when using parallel sequencing in order to reduce assembly time for example. From another side, the sequence should permit the assembly of the required volume suggested by the industrialization engineers. In this chapter, we will define the basis consisting on how determining the assembly time using the ASML defined in the previous chapter, then the assembly motions time standards definition on which every assembly time will be based. These assembly time estimation standards will represent an information data base of time values considering the parts characteristics impacting the time for the concerned motion such as the symmetry, the thickness, the surface, the easiness to reach and to handle.

5.2. Time estimation based on a sequencing using the ASML

The time estimation based on the assembly representation using this representation will depend on the time estimation of each motion in the sequence (table 6). The assembly time of a motion depends on the part to assemble characteristics, and on the technology used whether manual, automatic, or robotic. In fact every motion will be evaluated independently for manual, for automatic, and for robotic assembly and considering the part characteristics involved on the motion duration as the symmetry, the thickness, the surface, the easiness to reach and to handle. These timings will be defined later.

For an estimation using the ASML, we will make hypothesis that no stop time or wait exists, so a lean execution is supposed. Consequently, the transitions in the representation have no duration and their time is estimated to zero seconds. The assembly time is determined only from the motions in the sequence timings.

From a sequencing point of view using the ASML, the time depends on whether tasks are in serial or in parallel. If an action i and an action j are executed in serial, the time estimation of the group is the sum of the time estimation of each action (figure 25.a). And if they are executed in parallel, the time estimation of the group is the max between the timings of both i and j (figure 25.b). If there is a choice between two possible sub-sequences according to conditions the time estimation of the group is also the max between the timings between the two sub-sequences (figure 25.c).

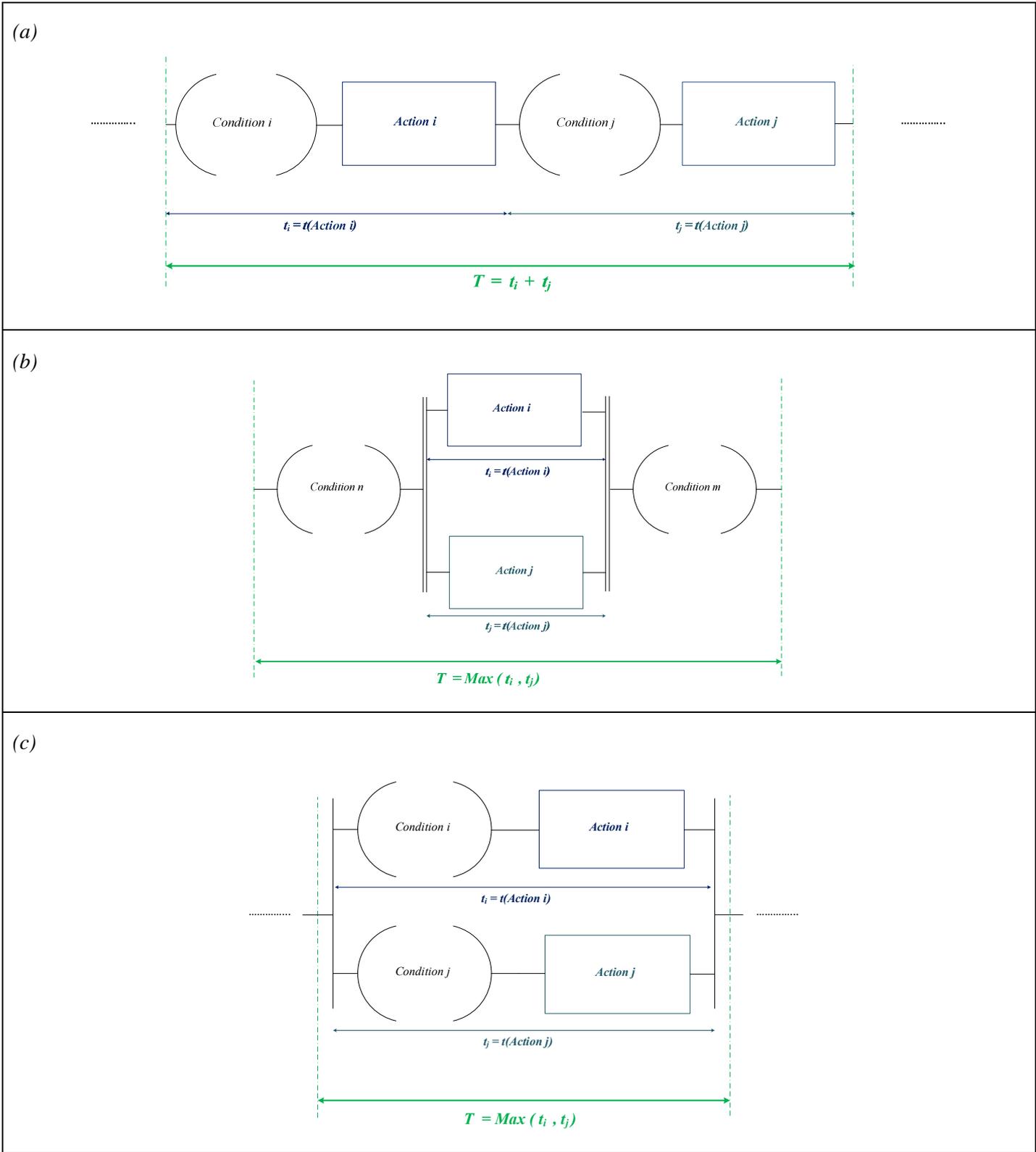


Figure 25: The elementary rules for sequences time estimation using an ASML representation

The figure 26 shows how determining the assembly time for 2 examples (a) and (b) where combinations of serial and parallel tasks exist.

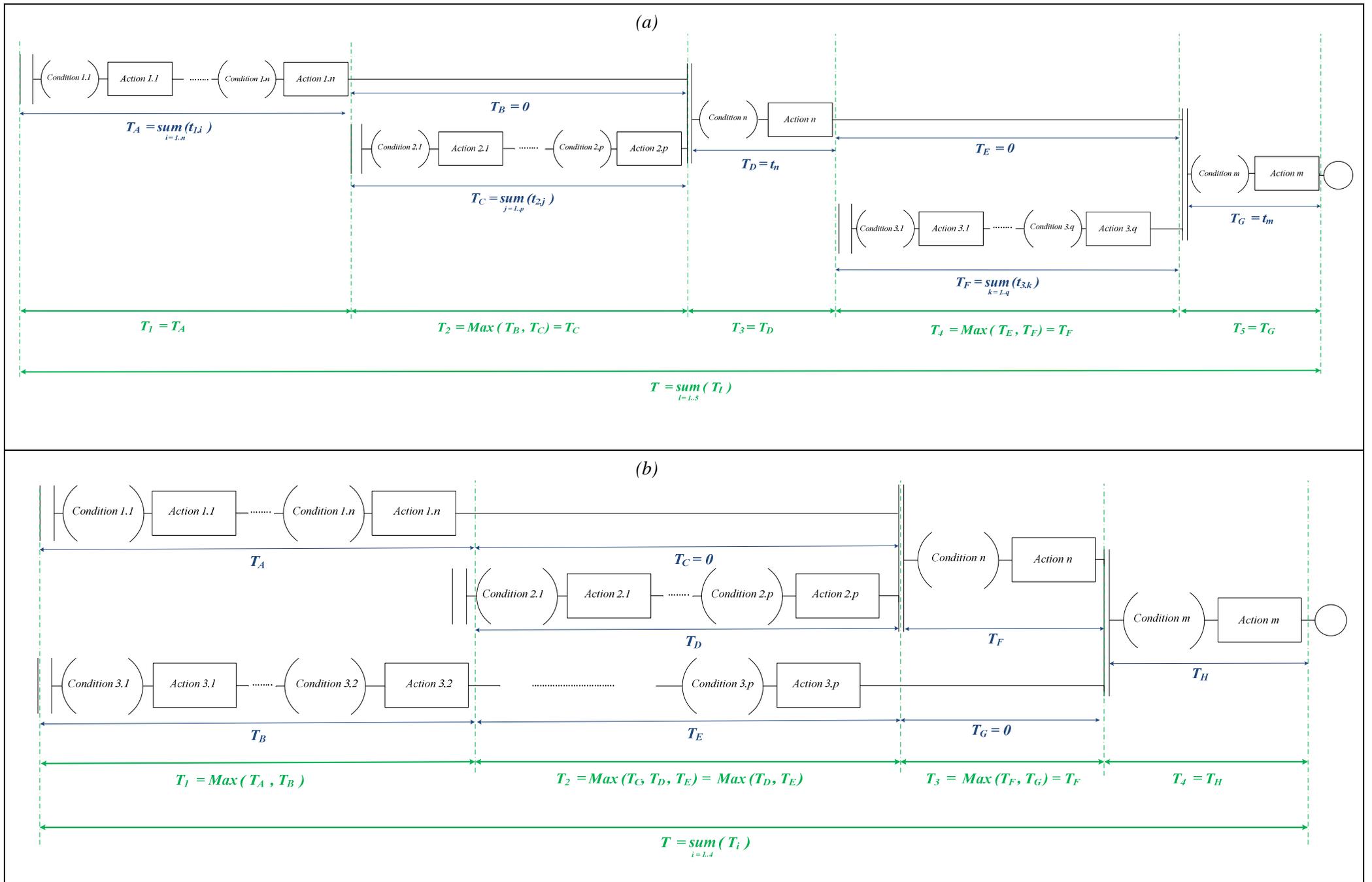


Figure 26: Examples of time determination using the ASML representation

5.3. Time estimation of assembly standardized motion

In the precedent section the basis of the assembly time estimation based on a representation using the ASML were defined. In fact, it was shown that this time estimation is impacted by the architecture and organization of the motion in the sequence which may be in serial, in parallel with an AND or OR divergence, or presenting a lag. From another side, it was defined that the time estimation is deduced in the sequence from the motions that forms the sequence, so from the time estimation of each motions or assembly actions written in each step of the representation using the ASML.

In the section 4.4.3, these assembly actions were standardized for the ASML and summarized in the table 6. One of the advantages of using a structured and standardized vocabulary which allow the description of every motion in the assembly is the standardized time estimation. In order to make the time estimation of an assembly sequence represented using the ASML and its vocabulary of standardized motions, it is necessary to estimate the time for each motion of these standardized motions. This will lead to an assembly timing standards building. This will be presented in this section.

The standardized timings to be built will be defined for all the assembly actions defined in the table 6. For each motion, the factors consisting in the characteristics of the product part to assemble that impact the required time to execute this motion will be defined with the separate ranges of values of each factor. The required time for each motion will be a function of the correlated factors and ranges.

As the purpose is the decision about automation, and considering the fact that each motion of the standardized verbs used in the assembly sequence representation may be realized in manual, in automatic, or in robotic, the time estimation for the assembly motions will be realized separately for manual, automatic, and robotic. To estimate an assembly sequence or subsequence represented using the ASML, the user has to refer to the corresponding motion with the corresponding involved factors according to part characteristics and the corresponding technology.

The table 1 Appendix contains time estimations for the three technologies for all the standardized verbs, and a coding system is to be used in the table in order to refer to the adequate timing. This coding system consists of three codes:

- The verb code consists in the number of the verb in the range ['1'.. '33']
- The technology to use code that may be 'M' as Manual, 'A' as Automatic, or 'R' as Robotic.
- The factor influencing the assembly verb time execution, that can be according to the corresponding verb 'a', 'b', 'c',... If the verb is not influenced by factors leading to only one value, no factor influencing code is used.

5.3.1. Time estimation for Manual Assembly

The standardized assembly motions time estimation was realized for manual assembly and the sources used to estimate the motions required time are the Methods time measurement described in the Methods Time Measurements (MTM) presented in section 3.2.1.2, the Boothroyd's time standards described in section 3.2.1.1, some combinations of the motions defined in these sources as described below the table 1 Appendix, some time keepings recuperated from a mechanical assembly manufacturer, and some logical estimations with a personal assumption when no source exist for the motion time estimation. Some estimation have to be improved, verified, or validated further by doing industrial measurements, benchmarking, or investigations. The estimated time values are shown in the table 1 Appendix and the detailed sources are below the table.

5.3.2. Time estimation for Automatic Assembly

For the automatic assembly, sources were fewer comparing to those available for manual assembly. The source used for the insert verb was an adaptation from the Boothroyd's insertion time standards as described in the sources below the table 1 Appendix. These values were compared to their corresponding insertion time standard for manual factor by factor, and it was deduced a time conversion factor of 50% as an average in order to convert a timing from manual to its corresponding in automatic. This conversion factor was used to estimate the timing of many verbs in automatic by a deduction from manual with corresponding factors as described in the table 1 Appendix. For some verbs, when the assembly action in automatic is a computer instruction execution as operate verb, read, or identify, the time is estimated to 0 seconds because it is supposed to be in a microseconds scale to some milliseconds. For other verbs such as Lay or scan, the same duration as for manual is used (sources below table 1 Appendix for the detailed sources of estimation).

5.3.3. Time estimation for Robotic Assembly

The same approach of estimation as for automatic is used except that 40% for the conversion if deduction from manual is made, is retained (sources below table 1 Appendix for the detailed sources of estimation).

5.4. Time savings: a criteria for assembly tasks automating

After standardizing assembly motion and building time standards, time savings for manual comparing to automatic and robotic are worthwhile to build for each motion considering the impacting factors for each of them. These time savings may represent a significant mean to decide about automation. In fact, automating the tasks representing the greatest time savings may be an issue for the decision. It can be usable to automate also a sub-sequence of related tasks by summing the time savings for manual-automatic or for manual-robotic by opting for the one representing a considerable time saving.

Therefore, we built a table containing time savings manual-automatic and manual-robotic. The values are presented in table 2 of Appendix. The coding system described in 5.3 and used in table 1 Appendix is also used for table 2 Appendix building and the time savings values are represented as follow: “ $\Delta t_{Manual-Automatic} / \Delta t_{Manual-Robotic}$ ” (table 2 Appendix).

The time savings are considered for the assembly time optimization. However, the assembly system optimization does not depend only on the assembly time. In fact, reducing the required time by automating or robotizing may lead to a very expensive system or to an oversized system from volume and productivity point of view. For the assembly system optimization the required volume and the assembly system cost should be considered with an economic optimization as described before in the third chapter and in the decision methodology outline defined in figure 6.

The time estimations defined before will be used in the assembly cost determination and the time savings will be used for building heuristics building for tasks automation selection in the economic optimization.

5.5. Example of application

In order to apply the defined rules of time estimation and the standardized timings of the assembly motions related to the ASML, we estimate the assembly sequence of the truck assembly operating mode treated in the section 4.5. The time estimation will be based on the assembly sequence representation of figure 39. The purpose is to use the standards built in order to estimate the required assembly time of the sequence in manual assembly which is the case of the students training, estimating time of the same sequence for automatic assembly, for robotic assembly, and for a hybrid assembly with combinations of manual, automatic, and robotic assembly.

5.5.1. Estimation in full Manual Assembly

The time estimation in manual assembly will be determined in this section using the manual standard times built. We reproduce the figure 39 and we show in for each assembly motion the corresponding assembly time code (green color) in the figure 27.

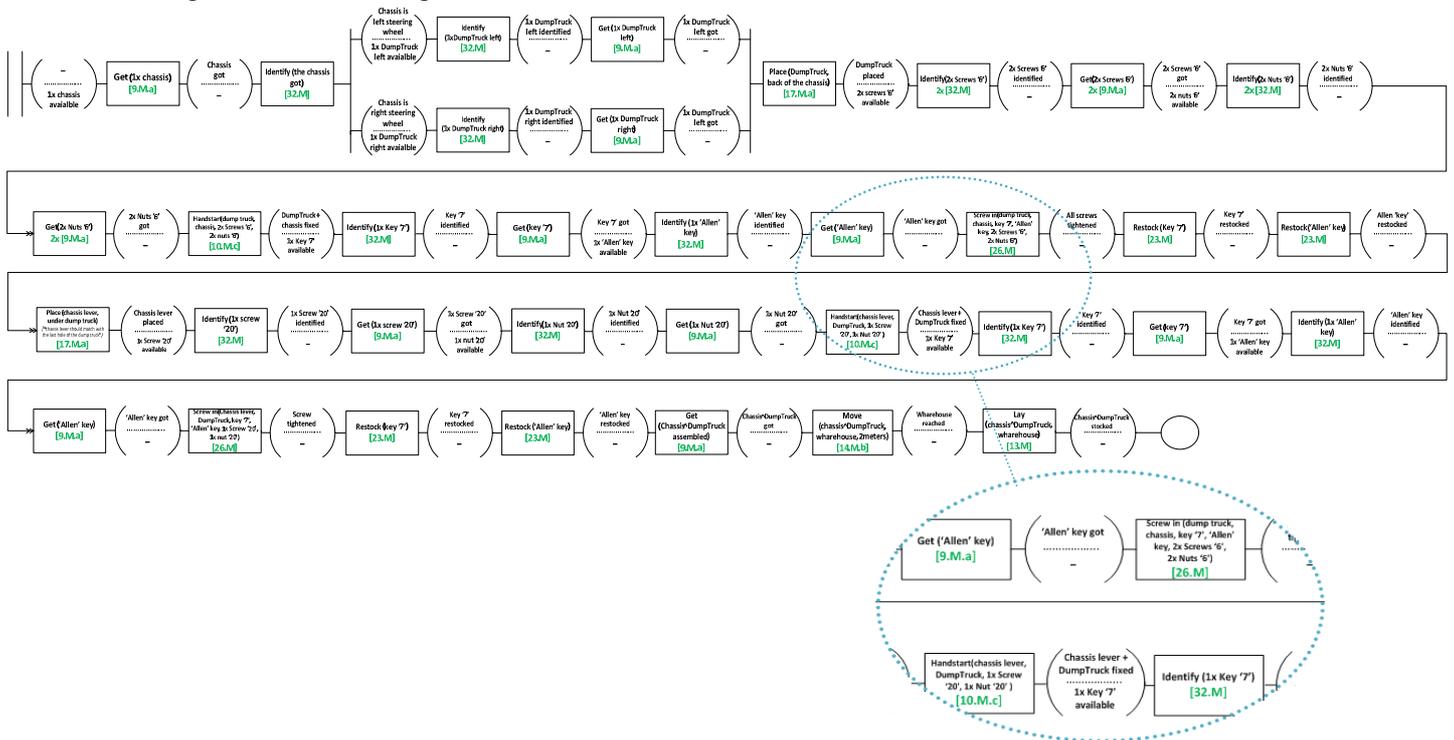


Figure 27: Example of time estimation of a full Manual assembly sequence

➔ The application of the defined rules and the use of the time standards defined in table 2 Appendix leads to an assembly required time in manual execution of : 108.46288 seconds \approx [1min , 48s , 463ms]

5.5.2. Estimation in full Automatic Assembly

Similarly, we estimate the assembly sequence of the truck in automatic assembly and we define the corresponding time codes in the figure 28.

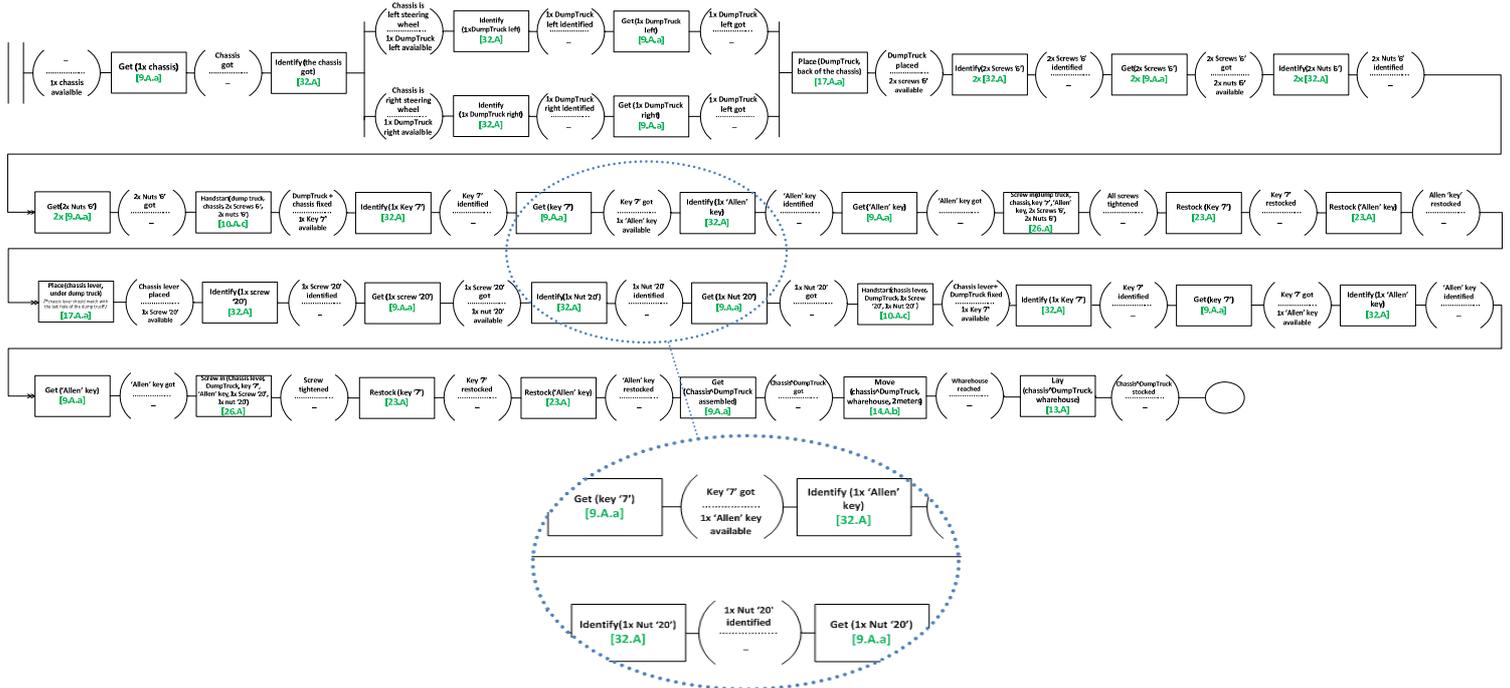


Figure 28: Example of time estimation of a full Automatic assembly sequence

➔ The estimated time of this sequence in automatic assembly is: 58.9642 seconds ≈ [0min , 58s , 964ms]

5.5.3. Estimation in full Robotic Assembly

We represent in the figure 29 the assembly sequence motions time codes for a robotic assembly.

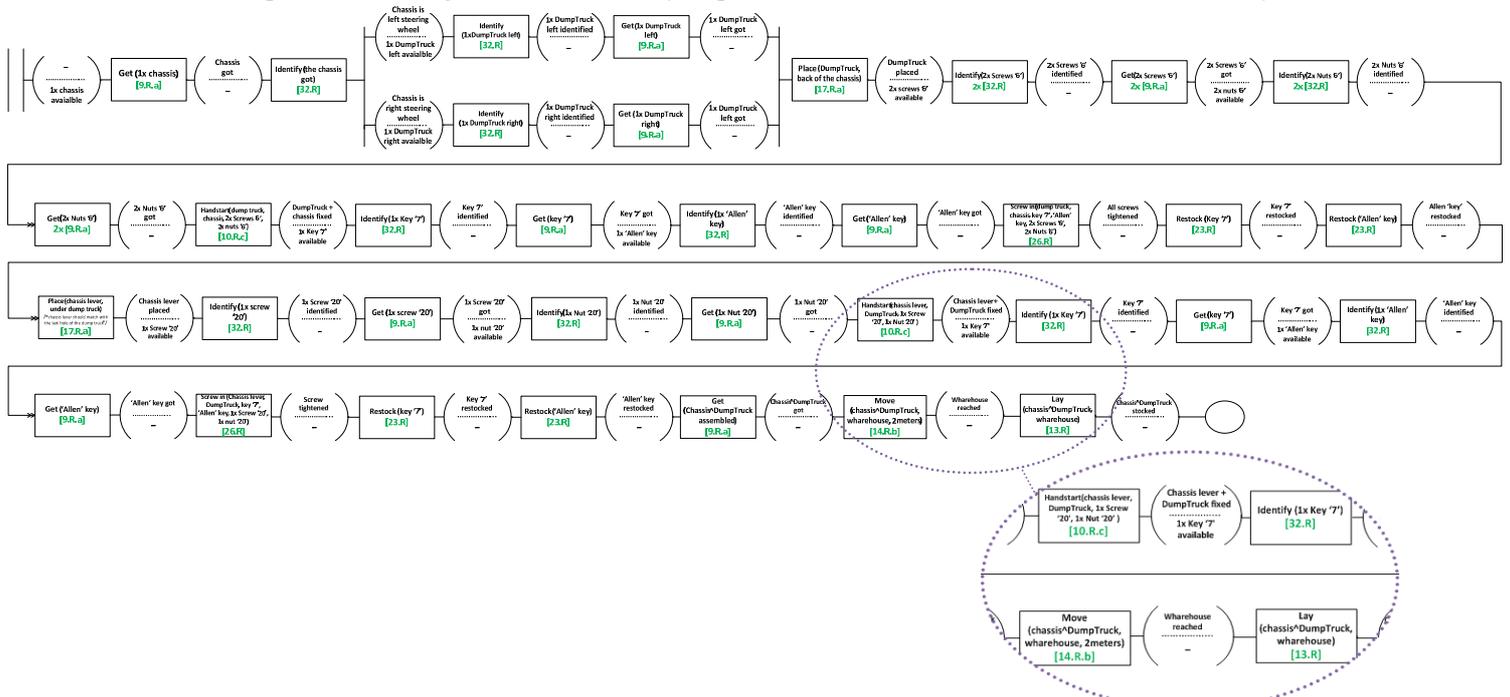


Figure 29: Example of time estimation of a full Robotic assembly sequence

➔ For this robotic assembly, the estimated time of the sequence is: 47.18953 seconds ≈ [0min , 47s , 190ms]

5.5.4. Estimation in Hybrid assembly

5.5.4.1. Hybrid Manual-Automatic assembly

The hybrid assembly system here is a manual assembly with an automated stocking of the final sub-product assembled as by a use of a conveyor. The figure 30 (a) represents the timing codes of each motion with its corresponding technology used whether is in manual or automatic.



Figure 30: Example of time estimation of a full Manual assembly sequence

→ For this hybrid assembly based on manual and automatic assembly the estimated time is: 107.728 seconds
≈ [1min , 47s , 728ms]

5.5.4.2. Hybrid Manual-Automatic-Robotic assembly

The hybrid assembly system that we define in this section is a mix of manual, automated, and robot assembly. The manual operations are defined in the part nature identification as in order to reduce cost and avoid vision sensors for identification which may be complex and costly to implement. The effective assembly is ensured by a robot. The final sub-product assembled evacuation and warehousing is ensured by simple automatic conveying system. The motions codes considering each the corresponding technology used for each assembly task are shown in the figure 30 (b).

→ The required time to execute the assembly using this hybrid system using manual, automatic, and robotic technologies seeming more productive than its previous hybrid but more costly is: 49.8736 seconds
≈ [0min , 49s , 864ms]

5.5.5. Interpretations

For the truck assembly training which was realized manually, the estimated time of the operating mode in manual assembly, is 1 minute, 48 seconds, and 463 milliseconds (section 5.5.1).

Using the modeling language that we built with the standardized assembly motions and the time standards using the time codes, the estimation of the assembly sequence time in automatic, robotic and hybrid system was possible.

The fastest solution is the robotic one, but it does not mean that it is the optimal solution or the optimal level of automation. In fact, that is because the time is not the only factor to judge and evaluate a solution. One of the other important factors to consider is the cost, and unfortunately, robots are generally the most expensive assembly systems, especially if they are used to be autonomous and to do self identification tasks in order to recognize objects or parts because it requires vision cameras and advanced sensors and software, and that's what exists in the beginning of the sequence where the robot have to recognize if the chassis got is a left or a right steering wheel, and to identify according to it a dump truck is left or right in order to start the assembly.

If we suppose that these identification systems are very expensive and cannot be purchasable by the manufacturer and at the same time that the quality or the volume requires a robot assembly, given that a full robotic assembly is the fastest solution with 47 min and 190 ms (section 5.5.3), one solution is to use a worker for the identification and a robot for only the assembly. The worker will identify the chassis and if it is a right steering wheel and will for example place it in a location x, and if it is a left, he will place it in a location y,, and the robot is programmed with two plans, assembly plan X if he detects a part in location x, and assembly plan Y if he detects an assembly plan y. For the warehousing (end of the assembly sequence), another hypothesis is that the robot used is so small so that he cannot move to place the final product to a distance of 2 meters, so an automatic conveyor is used to solve the problem. These hypothesis led to the hybrid system described in figure 30 (b) section 5.5.4.2 and to an estimated assembly time of [0min , 49s , 864ms] which is faster than the full automated and all other solutions except the full robotic, but supposed to be much cheaper because the identification is not ensured by the robot but manually by a worker, and the robot is smaller so cheaper than the robot used in the full robotic which is much bigger or using a self robotic conveyor allowing him to warehouse the final product located to 2 meters farer from the assembly station.

5.6. Conclusion

During this chapter, rules for determining assembly sequence time were defined for the assembly sequences modeling language (ASML) built before.

The standardized verbs defined and relative to the ASML were also estimated in this chapter from time point of view, and time standards were built for the verbs considering the factors that may impact each motion.

These motions were evaluated independently for manual, automatic, and robotic execution and time savings for manual-automatic and manual-robotic were calculated. These time savings may be used after in selecting tasks to automate presenting the most important time saving. Heuristics based on this principle may be defined as a perspective of the work in this axis.

At the end of the chapter, the assembly truck operating mode studied in the previous chapter was resumed and estimated from time point of view for full manual assembly, full automatic, full robotic, hybrid manual-automatic, and hybrid manual-automatic-robotic. The importance of the time issue using ASML was validated and the importance of the tool was argued in the example interpretation section.

CHAPTER 6. Conclusion and Outlooks

The research axis of this work is around the question “How to determine the optimal Level of Automation for Assembly Manufacturing Systems at an early stage of the manufacturing process before the system design?” The purpose was to define a methodology for supporting assembly systems conceivers and deciders within manufactories and helping them in the decision about the most suitable and optimized process with an adequate Level of Automation considering manufacturer intrinsic factors, parameters, product characteristics, and planned production.

In order to achieve this goal, the work started by a deep literature review in the topic. In fact, the literature directly related to the topic from decision making algorithms and methodologies point of view was not abundant. Consequently, an extensive literature related to the topic was established by crossing related subjects as assembly automation in the literature, automation and Level of Automation concept, the decision making about automation, and the different methodologies about automation available in the literature. The gathered information from the literature was organized and classified in this work and may represent a structured literature review reference in the research topic.

After the extensive review, a decision methodology outline about automation was built exploiting and combining the results found in the literature and extending these results to a decision methodology which seems to be suitable to combine the technical requirements, the product characteristics, the manufacturer context and capabilities, and the economic aspect. The methodology aims to structure the decision with respecting all the specific manufacturer requirements and offering the most profitable solution as possible.

To achieve this goal and make the methodology applicable, a graphical representation of assembly method is needed. After a review on the existent graphical methods used in assembly, and others that we described as usable for assembly representation, a need to build a new method dedicated to assembly sequences representation was raised. This led to the creation of a new Assembly Sequences Modeling Language labeled *ASML* with a standardized vocabulary of assembly motions and verbs. The modeling language was tested on an assembly example and proved as adequate and satisfactory for the decision about automation purpose.

In relation with the decision and optimization of the Level of automation, estimating assembly times is imperative. This is what led to a section about time rules building for the *ASML* allowing times estimation basing on an assembly representation using the modeling language *ASML*. In the same section, time standards were built for the assembly standardized motions for manual, automatic, and robotic assembly. This make possible to estimate assembly time for the assembly sequence, sub-sequence, or task in a defined technology leading to a final assembly estimation in full manual, full automatic, full robotic, or hybrid systems by making combinations of these previous. The obtained results prepared an adequate environment for the decision making by offering a complete and intuitive assembly standard modeling method.

The continuity of this work would be around building an accurate economic model for product assembly manufacturing cost calculation in manual, automatic, and robotic execution. This model cost is suggested to be the sum of elementary cost per assembly motion in the assembly representation model using *ASML* basing on the time required and the resource cost, and involving the *ASML* representation of the structure and the required investment. The economic model should consider also, as defined in the decision outline (figure 6), the industrialization requirements that may be known at an early stage of manufacturing such as volume, product market life, cycle times, down time estimated rate, and workers hourly rate according to the planned location.

Other axis may consider the pattern and algorithm for the detection of motions and tasks suggested to be worthwhile to be executed in manual, in automatic, or in robotic. In this work, we suggested the time savings, but other factors may be studied such as tasks execution complexity, tasks decreasing quality, tasks not suitable for a technology. This may be aided by feedbacks from experts and benchmarking. Algorithms for deducing the optimal *ASML* structure by serial or parallel execution of tasks that impacts directly the cost because it impacts the required resources for assembly. Rules have to be defined concerning technology dependencies for the standardized motions and precedence between motions imposing executing a task in the same technology as its precedent for some motions. The tool may be a learning computerized tool or an expert system with artificial intelligence using a base of rules and a base of facts in order to deduce the decision from the decision system inputs and rules.

For the work refinement, improving the built time standards is worthwhile. This may be performed by industrial measurements, timekeeping, and investigations in order to improve the time values accuracy, and by suggesting other parameters impacting the motions times with more precise ranges. The suggested accuracy may improve the decision methodology precision.

To conclude, the finality of the work would be the decision computerization and the creation of a decision support tool where the user draw the *ASML* assembly sequence in a software graphical interface and enter his inputs. The tool will according to the entered data calculate, optimize, and select each task in a defined technology following the decision methodology and calculate the assembly cost in each iteration. The result would be the assembly structure and technology of all the assembly tasks of the sequence which may be at the end manual, automatic, robotic, or hybrid fulfilling all the requirements and criteria entered as inputs, and optimizing the manufacturing cost in order to lead to the most profitable solution.

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Table of Appendices

Appendix 1	63
Appendix 1 tables	63
<u>Table 1: Assembly standardized motions time estimation for Manual, Automatic, and Robotic assembly</u>	64
<u>Table 2: Time savings for the standardized motion considering impacting factors</u>	71
Appendix 2	73
Appendix 2 Figures	74
<i>Figure 1: Flexible manufacturing system</i> [65]	74
<i>Figure 2: Architecture of Holonic Manufacturing systems</i> [69]	74
<i>Figure 3: Automated guided vehicle system with distributed agent based control</i> [83]	74
<i>Figure 4: Decentralised, self-organizing, and “Plug and Produce” – able material flow system</i> [27][28]	74
<i>Figure 5: Autonomous processes and enabling technologies</i> [60]	75
<i>Figure 6: Cooperative work place with location of the surveillance cameras</i> [4]	75
<i>Figure 7: Conceptual “Cobot” construction for flexible automotive assembly</i> [85]	75
<i>Figure 8: Product Life Cycle Management (PLM)</i> [99]	75
Appendix 3	76
Appendix 3 Figures	77
<i>Figure 9: Appropriate Level of Automation</i> [23]	77
<i>Figure 10: Graph of cost versus level of automation</i> [9]	77
Appendix 3 Tables	78
<u>Table 3: Levels of automation as defined by Frohm</u> [12]	78
<u>Table 4: LoA taxonomy according to Sheridan and Verplank, 1978</u> [32]	78
<u>Table 5: Hierarchy of levels of automation applicable to dynamic-cognitive and psychomotor control task performance</u> [33]	78
<u>Table 6: Scale of different levels of automation</u> [24,25]	78
Appendix 4	79
Appendix 4 Figures	80
<i>Figure 11: Effects of automation and design for assembly</i> [95]	80
<i>Figure 12: The basic technological alternatives in assembly</i>	80
<i>Figure 13: Combination of manual and automatic work station</i> [43]	81
<i>Figure 14: The methodology developed by Parasuraman</i> [25]	81
<i>Figure 15: Levels of automation for the independent functions</i> [25]	81
<i>Figure 16: The methodology developed by Ross</i> [93] <i>Figure 12: The basic technological alternatives in assembly</i>	82
<i>Figure 17: The methodology developed by Ross</i> [93]	82
<i>Figure 18: The power plug to assemble studied by Boothroyd for decision about automation issue</i> [95]	83
<i>Figure 19: The manufacturing automation decision tool concept developed by Almannai</i> [59]	83
<i>Figure 20: The decision making framework built by Almannai</i> [59]	83
<i>Figure 21: The Dynamo methodology in eight steps</i> [12,13]	83
<i>Figure 22: Workshop to decide min and max LoA values in a case study</i> [10]	84
<i>Figure 23: The LoA matrix : application of a case study</i> [10]	84
<i>Figure 24: Task and operation optimization</i> [10]	84
<i>Figure 25: Annual vehicle quantity per employee in the 3 studied sites</i> [38]	84

Appendix 4 tables	85
Table 7: The MABA-MABA list [53]	85
Table 8: The studied companies case studies in automation issue [23]	85
Table 9: Processes comparison summary table [55].....	85
Table 10: The experience of some manufactories with automation (built from [23]).....	86
Table 11: Different parameters shown as a function of the LoA xaf [28].....	87
Table 12: Part cost and production capacity as function of the level of automation factor xaf for each of the production systems A-F [28].....	87
Table 13: Actual and recommended (optimal) levels of automation [38]	87
Table 14: Comparison of results of product cost for the different assembly systems [95].....	87
Table 15: Unit cost of the assembly of vehicles in the 3 studied sites [38].....	88
Table 16: Quality indices [38].....	88
Table 17: Optimal Levels of automation with regard to flexibility [38].....	88
Table 18: Optimal levels of automation [38]	88
Appendix 5	89
Appendix 5 Figures	90
Figure 26: scencegraph structure for an example in assembly [106].....	90
Figure 27: Hierarchical structure model for an example in assembly [108].....	90
Figure 28: Hierarchical structure of a product example in assembly [109].....	90
Figure 29: Hierarchical Relation Graph of a product example in assembly [109]	90
Figure 30: A product example to assemble [112].....	91
Figure 31: Relational model for the product assembly example shown in figure 30 Appendix [113].....	91
Figure 32: Graph of connections for product assembly example shown in figure 30 Appendix [113]	91
Figure 33: CSBARM model for a product assembly example [108].....	91
Figure 34: Example of precedence graph of the product assembly shown in figure 18 [95]	92
Figure 35: Precedence graph for an example and the use of procedures [109].....	92
Figure 36: the AND/OR Graph representation principle [113]	92
Figure 37: AND/OR graph of feasible assembly sequences for the product assembly example shown in Figure 38: Parts tree representation corresponding to a given liaison diagram for a product assembly example [111].....	92
Figure 38: Parts tree representation corresponding to a given liaison diagram for a product assembly example [111]	93
Figure 39: CSBAT models for a product assembly example [108].....	93
Figure 40: Liaison diagram of a product example in assembly [111].....	93
Figure 41: Elements of SFC [115]	94
Figure 42: Reference types in SFC modeling language [115].....	94
Figure 43: The GANTT modeling language applied on an example [116].....	94
Appendix 6	95
Appendix 6 Figures	96
Figure 44: Classification system for part features affecting manual handling time	96
Figure 45: Classification system for part features affecting manual insertion time	97
Figure 46: Geometrical classification for rotational parts	98
Figure 47: Geometrical classification for non rotational parts	99
Figure 48: Additional relative feeder costs for a selection of feeding difficulties	100
Figure 49: Relative workhead costs W_r for a selection of automatic insertion situations	101
Figure 50: Classification system and data base for a single-station one arm robot assembly system	102
Figure 51: Classification system and data base for a single-station two arm robot assembly system	103
Figure 52: Classification system and data base for a multi-station system	104
Figure 53: Methods-time data	105
Figure 54: Methods-time data (continued).....	106
Figure 55: Effect of age and weight upon walking time per foot at average effort level	107

Appendix 1: Time Standards building

Table 1:
Assembly standardized motions time estimation
for Manual, Automatic, and Robotic assembly

Time estimation [Seconds]																	
M		Time estimation for Manual Assembly (M)				A		Time estimation for Automatic Assembly (A)				R		Time estimation for Robotic Assembly (R)			
1	Align	Easy to handle		a	sym	1.717 ⁽¹⁾	Easy to handle		a	sym	0.858 ⁽³⁴⁾	Easy to handle		a	sym	0.687 ⁽³⁵⁾	
				b	½ sym	1.978 ⁽¹⁾			b	½ sym	0.989 ⁽³⁴⁾			b	½ sym	0.791 ⁽³⁵⁾	
				c	Non sym	1.911 ⁽¹⁾			c	Non sym	0.955 ⁽³⁴⁾			c	Non sym	0.764 ⁽³⁵⁾	
		Difficult to handle (thickness, weight, temperature, no features provided for the purpose)		d	sym	3.24 ⁽¹⁾	Difficult to handle (thickness, weight, no features provided for the purpose)		d	sym	1.62 ⁽³⁴⁾	Difficult to handle (thickness, weight, no features provided for the purpose)		d	sym	1.296 ⁽³⁵⁾	
				e	½ sym	4.932 ⁽¹⁾			e	½ sym	2.466 ⁽³⁴⁾			e	½ sym	1.973 ⁽³⁵⁾	
				f	Non sym	5.868 ⁽¹⁾			f	Non sym	2.934 ⁽³⁴⁾			f	Non sym	2.347 ⁽³⁵⁾	
2	Apply	Surface		a	S < 5 [cm ²]	3.0 ⁽³⁾	Surface		a	S < 5 [cm ²]	1.5 ⁽³⁴⁾	Surface		a	S < 5 [cm ²]	1.2 ⁽³⁵⁾	
				b	5 ≤ S < 50 [cm ²]	7.0 ⁽³⁾			b	5 < S < 50 [cm ²]	3.5 ⁽³⁴⁾			b	5 < S < 50 [cm ²]	2.8 ⁽³⁵⁾	
				c	50 ≤ S < 100 [cm ²]	11.0 ⁽³⁾			c	50 < S < 100 [cm ²]	5.5 ⁽³⁴⁾			c	50 < S < 100 [cm ²]	4.4 ⁽³⁵⁾	
				d	100 ≤ S ≤ 500 [cm ²]	16.675 ⁽³⁾			d	100 < S < 500 [cm ²]	8.337 ⁽³⁴⁾			d	100 < S < 500 [cm ²]	6.67 ⁽³⁵⁾	
3	Attach	30.22 ⁽²⁾				15.11 ⁽³⁴⁾				12.08 ⁽³⁵⁾							
4	Clean	Surface		a	S < 0.5 [m ²]	2.0 ⁽³⁾	Surface		a	S < 0.5 [m ²]	1.0 ⁽³⁴⁾	Surface		a	S < 0.5 [m ²]	0.8 ⁽³⁵⁾	
				b	0.5 ≤ S < 1 [m ²]	3.0 ⁽³⁾			b	0.5 ≤ S < 1 [m ²]	1.5 ⁽³⁴⁾			b	0.5 ≤ S < 1 [m ²]	1.2 ⁽³⁵⁾	
				c	1 ≤ S < 3 [m ²]	5.0 ⁽³⁾			c	1 ≤ S < 3 [m ²]	2.5 ⁽³⁴⁾			c	1 ≤ S < 3 [m ²]	2.0 ⁽³⁵⁾	
				d	3 ≤ S < 10 [m ²]	10.0 ⁽³⁾			d	3 ≤ S < 10 [m ²]	5.0 ⁽³⁴⁾			d	3 ≤ S < 10 [m ²]	4.0 ⁽³⁵⁾	
5	Connect	18.132 ⁽⁴⁾				9.066 ⁽³⁴⁾				7.2528 ⁽³⁵⁾							
6	Disengage	a	Easy to handle	0.412 ⁽⁵⁾	a	Easy to handle	0.206 ⁽³⁴⁾	a	Easy to handle	0.165 ⁽³⁵⁾							
		b	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	0.626 ⁽⁵⁾	b	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	0.313 ⁽³⁴⁾	b	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	0.250 ⁽³⁵⁾							
7	Engage	a	Easy to handle	0.412 ⁽⁶⁾	a	Easy to handle	0.206 ⁽³⁴⁾	a	Easy to handle	0.165 ⁽³⁵⁾							
		b	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	0.626 ⁽⁶⁾	b	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	0.313 ⁽³⁴⁾	b	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	0.250 ⁽³⁵⁾							

8	Exchange	Full container Weight	a	W <10 [Kg]	7.5 ⁽⁷⁾	Full container Weight	a	W <10 [Kg]	3.75 ⁽³⁴⁾	Full container Weight	a	W <10 [Kg]	3.0 ⁽³⁵⁾							
			b	10 ≤ W <50 [Kg]	15 ⁽⁷⁾		b	10 ≤ W <50 [Kg]	7.5 ⁽³⁴⁾		b	10 ≤ W <50 [Kg]	6.0 ⁽³⁵⁾							
			c	50 ≤ W <70 [Kg]	30 ⁽⁷⁾		c	50 ≤ W <70 [Kg]	15.0 ⁽³⁴⁾		c	50 ≤ W <70 [Kg]	12.0 ⁽³⁵⁾							
			d	70 ≤ W <100 [Kg]	40 ⁽⁷⁾		d	70 ≤ W <100 [Kg]	20.0 ⁽³⁴⁾		d	70 ≤ W <100 [Kg]	16.0 ⁽³⁵⁾							
9	Get (without moving : distance ≤ 1 meter)	a	Small, medium, or large object easily grasped (thickness > 2mm)		0.2868 ⁽⁸⁾	a	Small, medium, or large object easily grasped (thickness > 2mm)		0.143 ⁽³⁴⁾	Part can be gripped and inserted using standard gripper or gripper used for previous part	a	Small, medium, or large object easily grasped (thickness > 2mm)		0.1147 ⁽³³⁾						
			b	Very small object or tool (thickness ≤ 2mm)			0.5388 ⁽⁸⁾	b	Very small object or tool (thickness ≤ 2mm)			0.269 ⁽³⁴⁾	b	Very small object or tool (thickness ≤ 2mm)		0.2155 ⁽³³⁾				
				c	Object jumbled with other objects so that select occur		0.428 ⁽⁸⁾		c			Object jumbled with other objects so that select occur		0.214 ⁽³⁴⁾	c	Object jumbled with other objects so that search and select occur		0.171 ⁽³³⁾		
																Part requires change to special gripper	d	Small, medium, or large object easily grasped (thickness > 2mm)		2.2147 ⁽³³⁾
									e	Very small object or tool (thickness ≤ 2mm)		2.3155 ⁽³³⁾								
										f	Object jumbled with other objects so that search and select occur		2.271 ⁽³³⁾							
10	Handstart	Easy to handle	a	sym	35.937 ⁽⁹⁾	Easy to handle	a	sym	17.9685 ⁽⁴⁰⁾		Easy to handle	a	sym	14.3748 ⁽⁴⁰⁾						
			b	½ sym	36.198 ⁽⁹⁾		b	½ sym	18.099 ⁽⁴⁰⁾	b		½ sym	14.4792 ⁽⁴⁰⁾							
			c	Non sy	36.131 ⁽⁹⁾		c	Non sy	18.065 ⁽⁴⁰⁾	c		Non sy	14.4524 ⁽⁴⁰⁾							
		Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	d	sym	37.46 ⁽⁹⁾	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	d	sym	18.73 ⁽⁴⁰⁾	Difficult to handle (thickness, weight, temperature, no features provided for the purpose)	d	sym	14.984 ⁽⁴⁰⁾							
			e	½ sym	39.152 ⁽⁹⁾		e	½ sym	19.576 ⁽⁴⁰⁾		e	½ sym	15.6608 ⁽⁴⁰⁾							
			f	Non sy	40.088 ⁽⁹⁾		f	Non sy	20.044 ⁽⁴⁰⁾		f	Non sy		16.0352 ⁽⁴⁰⁾						

Insert

After assembly no holding down required to maintain orientation and location	Easy to align and position during assembly	No resistance to insertion	a	Can easily reach the desired location	1.5 (10)	After assembly no holding down required to maintain orientation and location	Easy to align and position	No resistance to insertion	a	Straight line insertion	1.1 (31)	Part can be gripped and inserted using standard gripper or gripper used for previous part	No holding down	Self aligning	a	Using motion along or about one axis	1.0 (32)					
			b	Cannot easily reach the desired location	4.75 (10)				b	Insertion not straight line motion	2.0 (31)				b	Involving motion along or about more than one axis	1.8 (32)					
		Resistance to insertion	c	Can easily reach the desired location	2.5 (10)			Resistance to insertion	c	Straight line insertion	1.55 (31)			Not easy to align	c	Using motion along or about one axis	1.07 (32)					
			d	Cannot easily reach the desired location	5.75 (10)				d	Insertion not straight line motion	3.0 (31)				d	Involving motion along or about more than one axis	1.9 (32)					
		Not Easy to align or position during assembly	No resistance to insertion	e	Can easily reach the desired location			2.5 (10)	Not Easy to align or position (no features provided for the purpose)	No resistance to insertion	No resistance to insertion			e	Straight line insertion	1.55 (31)	Part require temporary holding or clamping	Self aligning	e	Using motion along or about one axis	1.0 (32)	
				f	Cannot easily reach the desired location			5.75 (10)						f	Insertion not straight line motion	3.0 (31)			f	Involving motion along or about more than one axis	1.8 (32)	
	Resistance to insertion	Resistance to insertion	g	Can easily reach the desired location	3.5 (10)	Resistance to insertion	g	Straight line insertion			2.4 (31)		Not easy to align	Not easy to align	g	Using motion along or about one axis		1.07 (32)				
			h	Cannot easily reach the desired location	6.75 (10)		h	Insertion not straight line motion			4.6 (31)				h	Involving motion along or about more than one axis		1.9 (32)				
	Holding down required during subsequent processes to maintain orientation at location	Easy to align and position during assembly	No resistance to insertion	i	Can easily reach the desired location	5.5 (10)	Holding down required during subsequent processes to maintain	Easy to align and position			No resistance to insertion		i	Straight line insertion	1.45 (31)	Part requires change to special gripper		No holding down	Self aligning	i	Using motion along or about one axis	3.1 (32)
													j	Insertion not straight line motion	2.7 (31)					j	Involving motion along or about more than one axis	3.9 (32)
														Not	k		Using motion	3.17 (32)				

16	Operate	1.0 ⁽¹⁴⁾			0.0 ⁽³⁶⁾			0.0 ⁽³⁶⁾					
17	Place	a	Move object to exact location	0.324 ⁽¹⁵⁾	a	Move object to exact location	0.162 ⁽³⁴⁾	a	Move object to exact location	0.130 ⁽³⁵⁾			
		b	Move object to approximate OR indefinite location	0.3096 ⁽¹⁵⁾	b	Move object to approximate OR indefinite location	0.155 ⁽³⁴⁾	b	Move object to approximate OR indefinite location	0.124 ⁽³⁵⁾			
18	Press (Switch/Button)	0.3132 ⁽¹⁶⁾			Press (Switch/Button) is supposed to be a Manual action: not available for automatic and robotic: sensors are used for presence detection or operating tasks for that issues			Press (Switch/Button) is supposed to be a Manual action: not available for automatic and robotic: sensors are used for the presence detection and operating tasks for that issues					
19	Push	1.4184 ⁽¹⁷⁾			0.709 ⁽³⁴⁾			0.567 ⁽³⁵⁾					
20	Read	Number of words	a	NW<5 [Words]	0.5 ⁽¹⁸⁾		0.0 ⁽³⁶⁾		0.0 ⁽³⁶⁾				
			b	5≤NW<10 [Words]	1.0 ⁽¹⁸⁾								
			c	10≤NW<25 [Words]	1.5 ⁽¹⁸⁾								
			d	25≤NW<50 [Words]	2.5 ⁽¹⁸⁾								
21	Remove (Preparatory)	25.0 ⁽¹⁹⁾			12.5 ⁽³⁴⁾			10.0 ⁽³⁵⁾					
22	Remove	24.176 ⁽²⁰⁾			12.088 ⁽³⁴⁾			9.6704 ⁽³⁵⁾					
23	Restock	8.0 ⁽³⁾			4.0 ⁽³⁴⁾			3.2 ⁽³⁵⁾					
24	Restrict	5.0 ⁽²¹⁾			2.5 ⁽³⁴⁾			2.0 ⁽³⁵⁾					
25	Scan	2.0 ⁽²²⁾			2.0 ⁽²²⁾			2.0 ⁽²²⁾					
26	Screw in	12.0 ⁽²³⁾			Screw in is supposed to be completely Manual, use 'Tighten' motion for automatic and robotic (using a torque tool)			Screw in is supposed to be completely Manual, use 'Tighten' motion for automatic and robotic (using a torque tool)					
27	Secure	30.22 ⁽²⁴⁾			15.11 ⁽³⁴⁾			12.088 ⁽³⁵⁾					
28	Snap	5.0 ⁽²⁵⁾			2.5 ⁽³⁴⁾			2.0 ⁽³⁵⁾					
29	Tighten	4.0 ⁽⁴³⁾			2.0 ⁽³⁴⁾			1.6 ⁽³⁵⁾					
30	Unscrew	a	Aided with a torque tool	4.0 ⁽²⁶⁾	2.0 ⁽³⁸⁾			1.6 ⁽³⁸⁾					
		b	Completely manually	12.0 ⁽²⁷⁾									
31	Walk	Distance	a	5 m	2.95272 ⁽¹²⁾	Distance	a	5 m	1.47636 ⁽³⁷⁾	Distance	a	5 m	1.181088 ⁽³⁷⁾
			b	6 m	3.543264 ⁽¹²⁾		b	6 m	1.771632 ⁽³⁷⁾		b	6 m	1.417304 ⁽³⁷⁾
			c	7 m	4.133808 ⁽¹²⁾		c	7 m	2.067 ⁽³⁷⁾		c	7 m	1.65352 ⁽³⁷⁾
			d	8 m	4.724352 ⁽¹²⁾		d	8 m	2.362176 ⁽³⁷⁾		d	8 m	1.889 ⁽³⁷⁾
			e	9 m	5.314896 ⁽¹²⁾		e	9 m	2.657448 ⁽³⁷⁾		e	9 m	2.1259 ⁽³⁷⁾
			f	10 m	5.90544 ⁽¹²⁾		f	10 m	2.95272 ⁽³⁷⁾		f	10 m	2.36217 ⁽³⁷⁾
32	Identify	1.0 ⁽²⁸⁾			0.0 ⁽³⁶⁾			0.0 ⁽³⁶⁾					
33	Wait	0.0 ⁽³⁰⁾			0.0 ⁽³⁰⁾			0.0 ⁽³⁰⁾					

- **Sources and justifications about the motions time estimation:**

- (1) *MTM figure 21 Appendix, “Position” motion average values of classes 1 and 3, multiplied by 0.036 (units conversion from TMU to seconds)*
- (2) *Industrial mechanical assembly manufacturer timekeeping average values: technical files of timekeeping*
- (3) *Inspirations and adaptations from (2)*
- (4) *Standard verb ‘Attach’ timing (table 1 Appendix) multiplied by 0.6 as adaptation factor*
- (5) *MTM figure 21 Appendix “disengage” motion average value, multiplied by 0.036 (units conversion from TMU to seconds)*
- (6) *Almost same duration as standard verb ‘Engage’ from required timing point of view (table 1 Appendix)*
- (7) *‘Exchange’ concerns only the change of empty (container) by full (container) and don’t concern the move or walk, these motions if exists are treated separately by the assembly representation using the ASML, the ‘exchange’ motion is estimated by personal estimation*
- (8) *‘Get’ does not consider the move or walk but consists only on the action of getting a part, tool,... It is estimated to “Reach” + “Grasp” of the MTM (personal estimation):*
 - *“Reach”: MTM figure 20 Appendix “Reach” motion for 4 Inches configuration (≈ 1 meter) average value for all classes, multiplied by 0.036 (units conversion from TMU to seconds) leading to 0.2256 seconds*
 - *“Grasp”: MTM figure 21 Appendix “Grasp” motion values of classes 1a, 1b, and 4, multiplied by 0.036 (units conversion from TMU to seconds) leading to 0.2028 seconds*
- (9) *Sum of motions timings ‘Align’(table 1 Appendix), ‘Attach’(table 1 Appendix), and ‘Tighten’(table 1 Appendix) for each configuration of part characteristics (personal estimation)*
- (10) *Boothroyd “Manual Insertion Times” (figure 12 Appendix).*
For “part and associated tool cannot easily reach desired location”, average values are calculated from the two varieties “due to obscured access or restricted vision” and “due to obscured access and restricted vision” because sense and values are almost the same for these varieties.
- (11) *Equivalent to ‘easy Grasp’ in the MTM (personal estimation) : class ‘1a’ in the MTM figure 21 Appendix, multiplied by 0.036 (units conversion from TMU to seconds)*
- (12) *Calculated basing on the MTM curve presented in the figure 22 Appendix “Walking” motion calculated with the following parameters: weight 175 pounds, age 25 to 34, distance 4 meters. Remembering that 1m = 3.2808 feet, and 1 hour = 3600 seconds, we deduce that $0.00005 \text{ hours/foot} = 0.00005 \times (3600 \times 3.2808) \text{ seconds/meters} = 0.590544 \text{ seconds/meters}$. For n meters we obtain $\text{Move} = n \times 0.590544 \text{ seconds}$*
- (13) *‘Open preparatory’ is estimated to 45 seconds (personal estimation) consisting of handling packaging, separating layers, and opening to get content.*
- (14) *‘Operate’ is estimated to 1 second (personal estimation) consisting on activating an operation.*
- (15) *‘Place’ is estimated (personal estimation) to MTM “Move” motion for 4 Inches calculating the average (figure 20 Appendix) with converting TMU to seconds and Inches to meters + estimated “Lay” of table 1 Appendix*
- (16) *‘Press’ is estimated to MTM “Reach” motion (figure 20 Appendix) with for 10 Inches and the A class: ‘Reach to object in fixed location’ \approx Reaching (and pressing) the button*
- (17) *MTM figure 21 Appendix “Position” motion ‘class 3’ (Exact Heavy pressure required) and ‘symmetrical’ part because no rotation required for push, multiplied by 0.036 (units conversion from TMU to seconds)*
- (18) *‘Read’ consists on reading notices or indications, the required time for reading depends on the number of words (personal estimation)*
- (19) *‘Remove preparatory’ is same as Open preparatory from task duration point of view (personal estimation)*
- (20) *‘Remove’ is estimated to 80% of “Attach” motion in table 1 Appendix (personal estimation)*
- (21) *‘Restrict’ is estimated to 5 seconds (personal estimation) consisting on Measure and Cut of cables or easy parts*
- (22) *‘Scan’ is estimated to 2 seconds (personal estimation) consisting on only the scan operation : getting the scan machine and the object to scan is not considered because treated apart in the assembly sequence representation using the ASML*

- (23) 'Screw in' is estimated to 3x Tighten where tighten defined in table 1 Appendix (personal estimation): 'Screw in' is completely manual ≠ tighten is aided with a tool
- (24) 'Secure' is same as 'Attach' defined in table 1 Appendix from task duration point of view (personal estimation) consisting on fixing cables
- (25) 'Snap' is estimated to 5 seconds (personal estimation) consisting on clipping in parts
- (26) Same as 'Tighten' from task duration point of view (personal estimation) because executed with the aid of a tool (generally a torque tool)
- (27) Same as 'Screw in' from task duration point of view (personal estimation) because executed completely manually
- (28) 'Identify' is estimated to 1.0 seconds (personal estimation) consisting on identification of adequate needed tool, or part, or screws, etc...
- (29) Deduction from ⁽¹⁷⁾ (personal estimation)
- (30) Fictive action described in section 4.4.2 and estimated in 4.4.3. Its purpose is generally the respect of the ASML structure.
- (31) Boothroyd "Automatic Insertion Times" (figure 16 Appendix).
-For "Straight line insertion", average values are calculated from the two varieties "from vertically above" and "not from vertically above" because sense and values are almost the same for these varieties.
- (32) Boothroyd "Robot assembly data for a single station one arm system" (figure 17 Appendix).
-For "Using motion along or about one axis", average values are calculated from the two varieties "Using motion along or about the vertical axis" and "Using motion along or about a non vertical axis" because no need to separate between them and values are almost the same for these varieties.
-The time value results from the sum of "relative affective basic operation time" and "Relative time penalty for gripper or tool change". The "Relative time penalty for gripper or tool change" is different from zero only for "Part requires change to special gripper", it is equal to zero for the remaining variety: "part can be gripped and inserted using standard gripper or gripper used for previous part"
- (33) Inspired from 'Get' motion in manual (table 1 Appendix) for the values /coming from MTM/ (table 1 Appendix) by multiplication by 40% and from 'Inspect' motion in robotic /coming from Boothroyd tables for the organization and principle of dependence on changing grippers adding 2.1 seconds when need to change grippers (figure 18 Appendix).
- (34) This automatic task time is deduced from the same motion time in Manual execution as 50% of t_{Manual} supposed an average conversion from manual to automated assembly manufacturing (calculated as mean value for conversion of insertion time of Boothroyd timings for manual to automatic for equivalent motions and delicateness)
- (35) This robotic task time is deduced from the same motion time in Manual execution as 40% of t_{Manual} supposed an average conversion from manual to robotic assembly manufacturing (calculated as mean value for conversion of insertion time of Boothroyd timings for manual to robotic for equivalent motions and delicateness)
- (36) Cognitive task, program execution, or signal processing: duration is negligible because is on a scale of microseconds to some milliseconds: rounded to zero seconds
- (37) Use of a translating or conveying system, or just a displacement or a move for proportionally huge robots and systems. Time is estimated using ⁽³⁴⁾ for automatic assembly and ⁽³⁵⁾ for robotic assembly
- (38) Using ⁽³⁴⁾ for automatic assembly and ⁽³⁵⁾ for robotic assembly applied on the corresponding motion (unscrew) for the variety "Aided with a torque tool"
- (39) Action of scan consists on only the fact of scanning doesn't involve getting and aligning the scan machine. This action of scan is consists on a same mechanism or apparatus used in manual, automatic, robotic. The difference between manual, automatic, and robotic comes from the motions just before in the ASML representation as getting and aligning the apparatus with the product to scan in order to execute the scan task. The action of only scanning is estimated to 2.0 seconds for the three technologies.
- (40) Handstart is used as the first positioning of some delicate assembly tasks. Consequently it may be used for automatic and robotic. The times were estimated using ⁽³⁴⁾ and ⁽³⁵⁾.
- (41) Inspection becomes possible for automatic and robotic with the technology progress in the last few years using cameras, vision systems, pictures and videos analysis connected to a supervising computer via communication network and using data bases. The times of video or picture capture, signal processing, analysis, data base access, calculations and comparisons is estimated to 800 milliseconds (personal estimation).
- (42) 'Lay' don't depend on technology. Laying using a hand (manual) or a gripper or arm (automatic and robotic) is the same from duration point of view So timings are the same for automatic and robotic as for manual /coming from MTM/ for this motion (See ⁽¹¹⁾ : personal estimation).
- (43) 'Tightening' consists on screwing in using a torque tool or machine also for manual manipulating by hand the torque tool, a torque machine tool for automatic, and an arm equipped by a torque apparatus for robotic ≠ screw in which is fully manual. The time is estimated using ⁽³⁾.

Table 2:
Time savings for the standardized motion considering impacting factors

Time savings $\Delta t_{\text{Manual-Automatic}} / \Delta t_{\text{Manual-Robotic}}$ [Seconds]							
1. Align							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>		
0.858 / 1.03	0.989 / 1.187	0.955 / 1.147	1.62 / 1.944	2.466 / 2.959	2.934 / 3.521		
2. Apply							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>				
1.5 / 1.8	3.5 / 4.2	5.5 / 6.6	8.337 / 10.005				
3. Attach							
15.11 / 18.14							
4. Clean							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>				
1.0 / 1.2	1.5 / 1.8	2.5 / 3.0	5.0 / 6.0				
5. Connect							
9.066 / 10.879							
6. Disengage							
<i>a</i>	<i>b</i>						
0.206 / 0.247	0.313 / 0.376						
7. Engage							
<i>a</i>	<i>b</i>						
0.206 / 0.247	0.313 / 0.376						
8. Exchange							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>				
3.75 / 4.5	7.5 / 9.0	15.0 / 18.0	20.0 / 24.0				
9. Get							
<i>a</i>	<i>b</i>	<i>c</i>					
0.143 / 0.1721 ⁽³⁾	0.269 / 0.3233(-1.7767 ⁽³⁾)	0.214 / 0.257(-1.843 ⁽³⁾)					
10. Handstart							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>		
17.968 / 21.5622	18.099 / 21.7188	18.065 / 21.6786	18.73 / 22.476	19.576 / 23.4912	20.044 / 24.0528		
11. Insert							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>	<i>g</i>	<i>h</i>
0.4 / 0.5 ⁽⁴⁾	2.75 / 2.95 ⁽⁴⁾	0.96 / 1.43 ⁽⁴⁾	2.75 / 3.85 ⁽⁴⁾	0.95 / 1.5 ⁽⁴⁾	2.75 / 3.95 ⁽⁴⁾	1.1 / 2.43 ⁽⁴⁾	2.15 / 4.85 ⁽⁴⁾
<i>i</i>	<i>j</i>	<i>k</i>	<i>l</i>	<i>m</i>	<i>n</i>	<i>o</i>	<i>p</i>
4.05 / 2.4 ⁽⁴⁾	6.05 / 4.85 ⁽⁴⁾	4.45 / 3.33 ⁽⁴⁾	5.75 / 5.75 ⁽⁴⁾	4.45 / 3.4 ⁽⁴⁾	5.75 / 5.85 ⁽⁴⁾	4.35 / 4.365 ⁽⁴⁾	4.65 / 6.75 ⁽⁴⁾
12. Inspect							
1.96/1.96							
13. Lay							
0.0 / 0.0							
14. Move							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>				
0.29527 / 0.35433	0.590 / 0.70865	0.8858 / 1.06298	1.18105 / 1.41726				
15. Open (Preparatory)							
22.5/27.0							
16. Operate							
1.0 / 1.0							
17. Place							
<i>a</i>	<i>b</i>						
0.162 / 0.194	0.155 / 0.1856						
18. Press (Switch/Button)							
. ⁽¹⁾ / . ⁽¹⁾							
19. Push							
0.709 / 0.8514							
20. Read							
<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>				
0.5 / 0.5	1.0 / 1.0	1.5 / 1.5	2.5 / 2.5				
21. Remove (Preparatory)							
12.5/15.0							
22. Remove							
12.088 / 14.5056							
23. Restock							
4.0 / 4.8							

24. Restrict					
2.5 / 3.0					
25. Scan					
0.0 / 0.0					
26. Screw in					
10.0 ⁽²⁾ / 10.4 ⁽²⁾					
27. Secure					
15.11 / 18.132					
28. Snap					
2.5 / 3.0					
29. Tighten					
2.0 / 2.4					
30. Unscrew					
a			b		
2.0 / 2.4			10.0 / 10.4		
31. Walk					
a	b	c	d	e	f
1.476 / 1.7716	1.772 / 2.12596	2.067 / 2.48029	2.362 / 2.83535	2.657 / 3.189	2.953 / 3.54327
32. Identify					
1.0 / 1.0					
33. Wait					
0.0 / 0.0					

- **Notes: The exceptions in time savings:**

⁽¹⁾ Action supposed to be only manual and cannot be automated or robotized: no time saving for the motion

⁽²⁾ Calculated by subtraction with the verb “tighten” considered as the equivalent of “screw in” for automatic and robotic.

⁽³⁾ Calculated when change to special gripper is required for the execution of the concerned task in robotic assembly (see table 1 Appendix): value may be negative meaning the time lost (not a time saved) comparing to manual execution of the same task.

⁽⁴⁾ For the ‘Insert’ assembly motion time saving of manual via robotic, the factor consisting on part requiring change to special gripper (robotic) was instantiated to the factor holding down required to maintain orientation and location after assembly (manual) (see table 1 Appendix), because the time penalty impact of these factors is supposed to be the same

Appendix 2: Assembly Automation in the literature

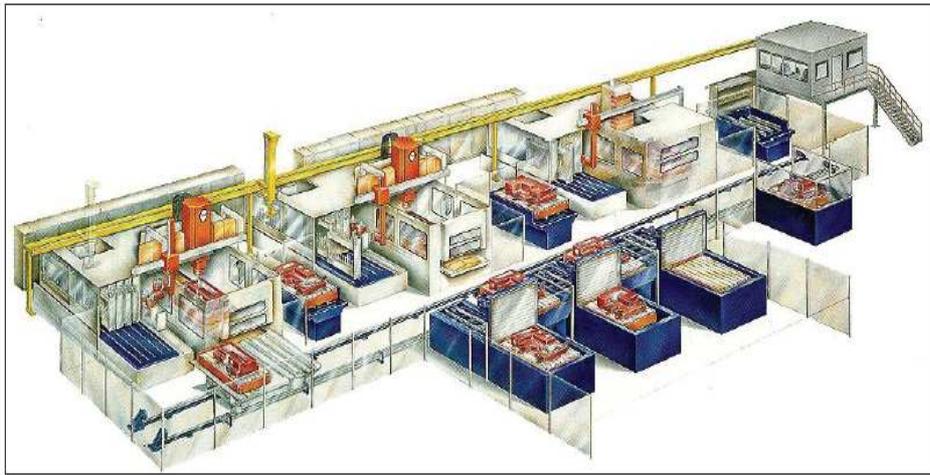


Figure 1: Flexible manufacturing system [65]

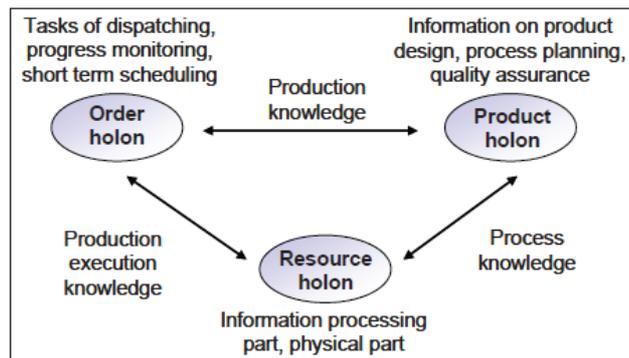


Figure 2: Architecture of Holonic Manufacturing systems [69]

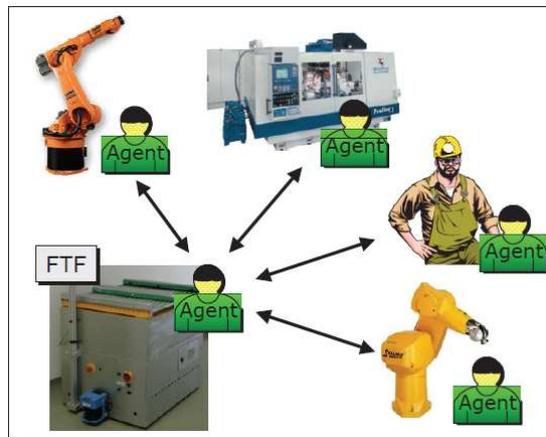


Figure 3: Automated guided vehicle system with distributed agent based control [83]

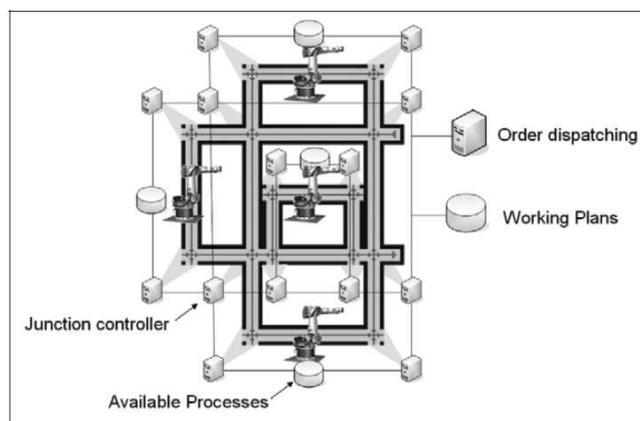


Figure 4: Decentralised, self-organizing, and "Plug and Produce" – able material flow system [27][28]

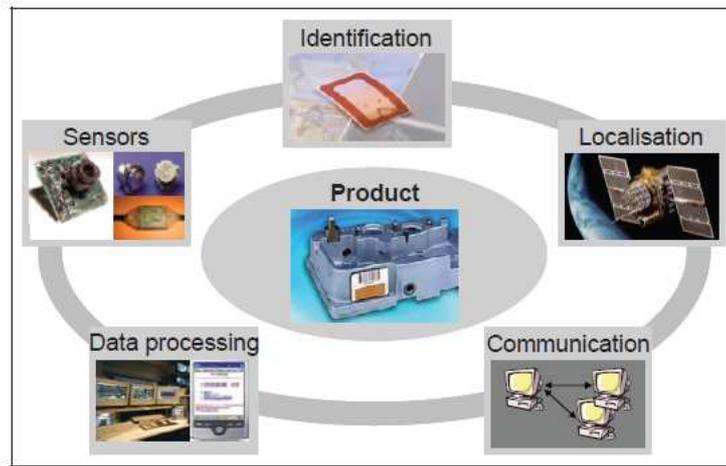


Figure 5: Autonomous processes and enabling technologies [60]

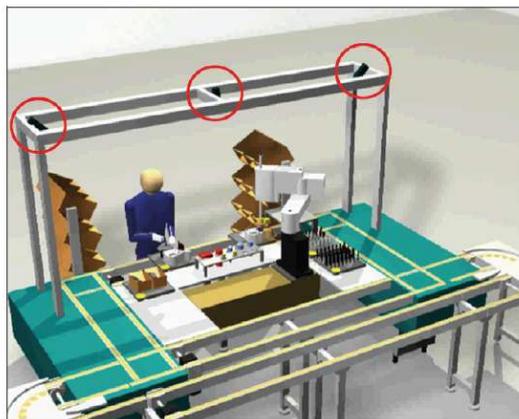


Figure 6: Cooperative work place with location of the surveillance cameras [4]

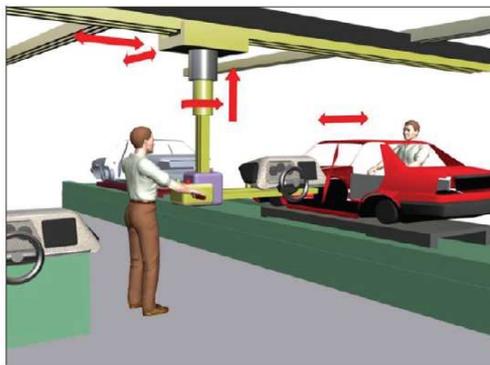


Figure 7: Conceptual "Cobot" construction for flexible automotive assembly [85]

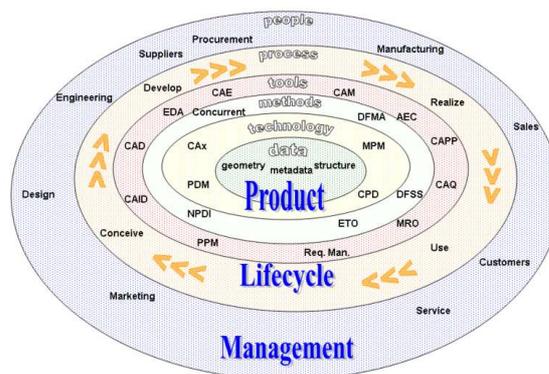


Figure 8: Product Life Cycle Management (PLM) [99]

Appendix 3: Level of Automation in the literature

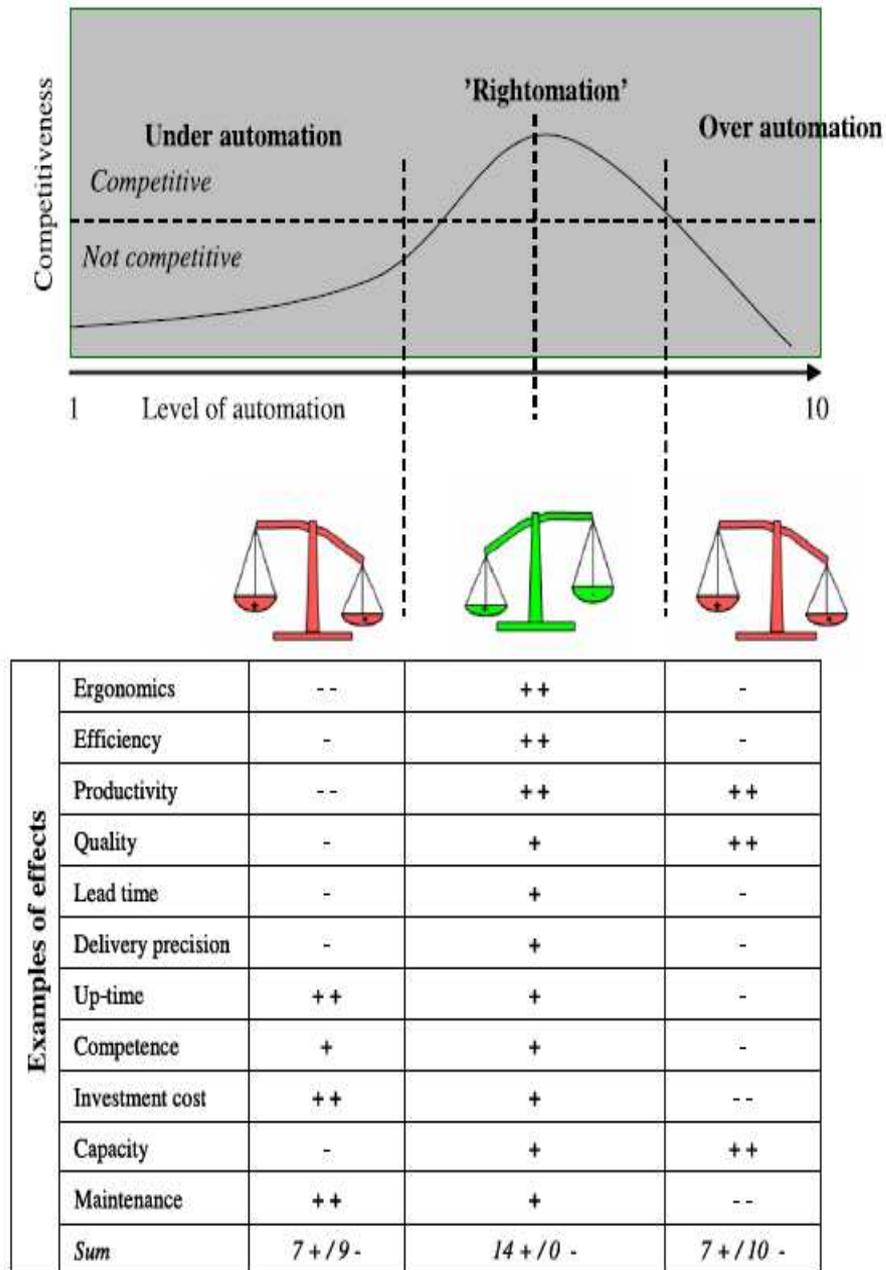


Figure 9: Appropriate Level of Automation [23]

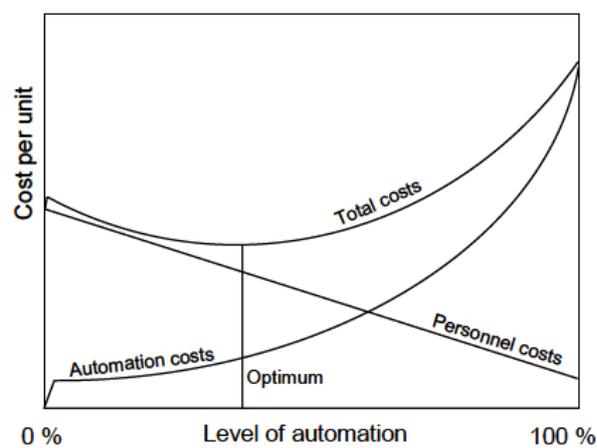


Figure 10: Graph of cost versus level of automation [9]

Table 3: Levels of automation as defined by Frohm [12]

LoA	Mechanical	Information
1	Totally manual	Totally manual
2	Static hand tool	Decision giving
3	Flexible hand tool	Teaching
4	Automated hand tool	Questioning
5	Static machine/workstation	Supervision
6	Flexible machine/workstation	Intervene
7	Totally automatic	Totally automatic

Table 4: LoA taxonomy according to Sheridan and Verplank, 1978 [32]

LoA	Explanation
1	Human does the whole job up to the point of turning it over to the computer to implement
2	computer helps by determining the options
3	computer helps to determine options and suggests one, which human need not follow
4	computer selects action and human may or may not do it;
5	computer selects action and implements it if human approves
6	computer selects action, informs human in plenty of time to stop it
7	computer does whole job and necessarily tells human what it did
8	computer does whole job and tells human what it did only if human explicitly asks
9	computer does whole job and decides what the human should be told
10	computer does the whole job if it decides it should be done, and if so, tells human, if it decides that the human should be told

Table 5: Hierarchy of levels of automation applicable to dynamic-cognitive and psychomotor control task performance [33]

Level of automation	Roles			
	Monitoring	Generating	Selecting	Implementing
(1) Manual control (MC)	Human	Human	Human	Human
(2) Action support (AS)	Human/Computer	Human	Human	Human/Computer
(3) Batch processing (BP)	Human/Computer	Human	Human	Computer
(4) Shared control (SHC)	Human/Computer	Human/Computer	Human	Human/Computer
(5) Decision support (DS)	Human/Computer	Human/Computer	Human	Computer
(6) Blended decision making (BDM)	Human/Computer	Human/Computer	Human/Computer	Computer
(7) Rigid system (RS)	Human/Computer	Computer	Human	Computer
(8) Automated decision making (ADM)	Human/Computer	Human/Computer	Computer	Computer
(9) Supervisory control (SC)	Human/Computer	Computer	Computer	Computer
(10) Full automation (FA)	Computer	Computer	Computer	Computer

Table 6: Scale of different levels of automation [24,25]

Level	Explanation
1	The computer offers no assistance; humans must do it all.
2	The computer offers a complete set of action alternatives, and
3	Narrows the selection down to a few, or
4	Suggests one, and
5	Executes that suggestions of humans approve, or
6	Allows humans a restricted time to veto before automatic execution, or
7	Executes automatically, then necessarily informs humans, or
8	Informs them after the execution only if they ask, or
9	Informs them after execution if it, the computer, decides to.
10	The computer decides everything and acts autonomously, ignoring humans.

Appendix 4: Decision about automation in the literature

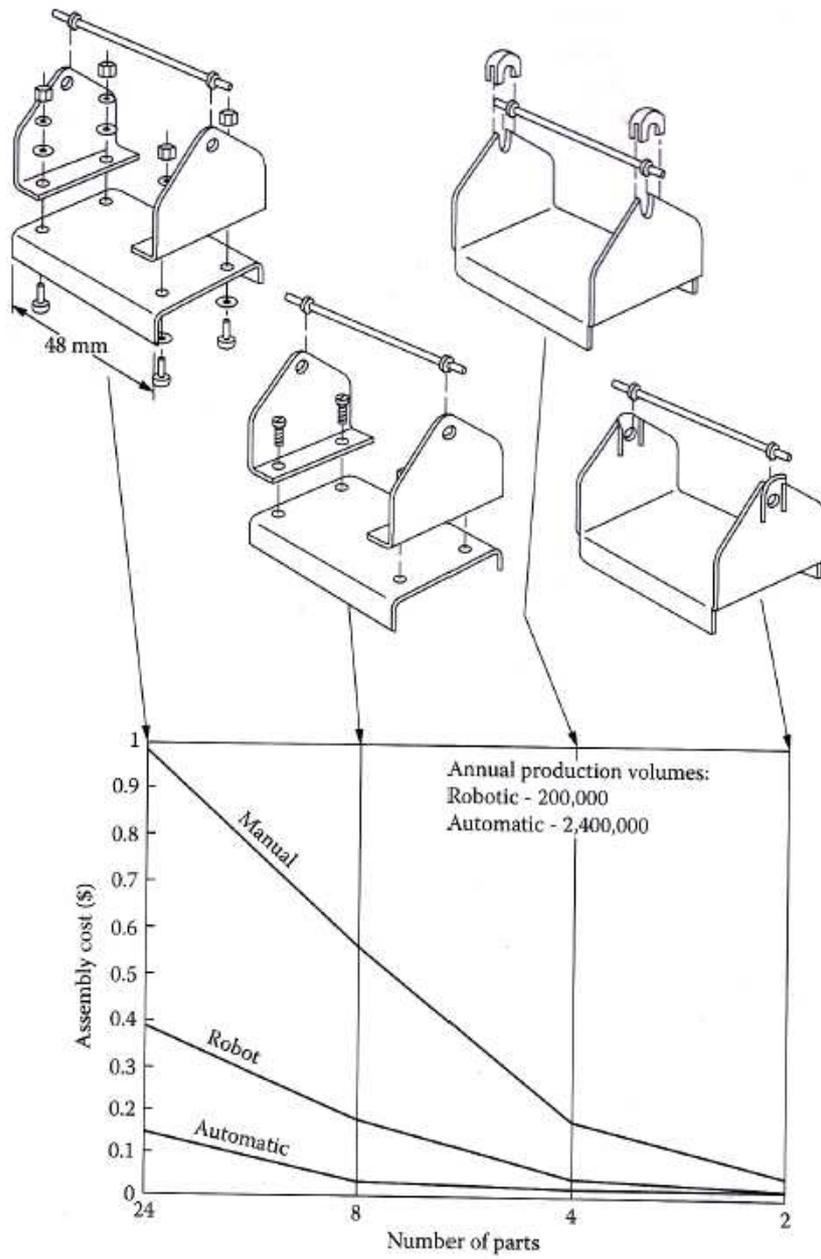


Figure 11: Effects of automation and design for assembly [95]

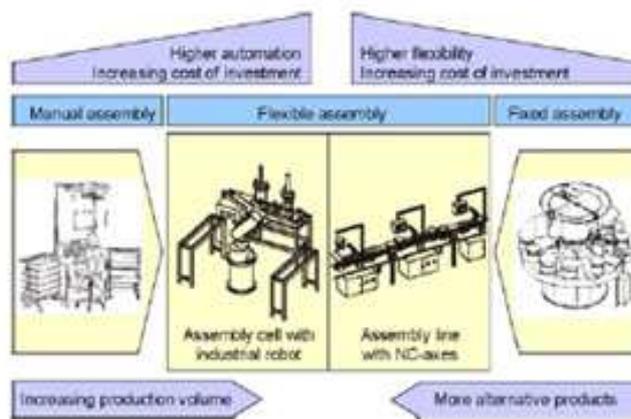


Figure 12: The basic technological alternatives in assembly

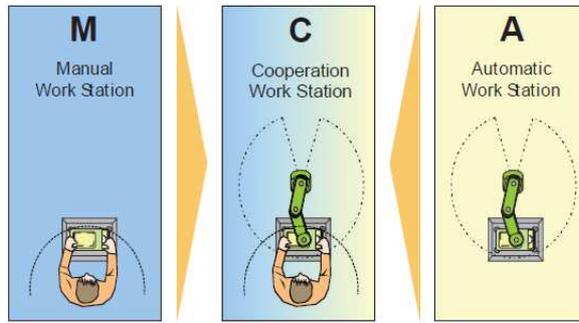


Figure 13: Combination of manual and automatic work station [43]

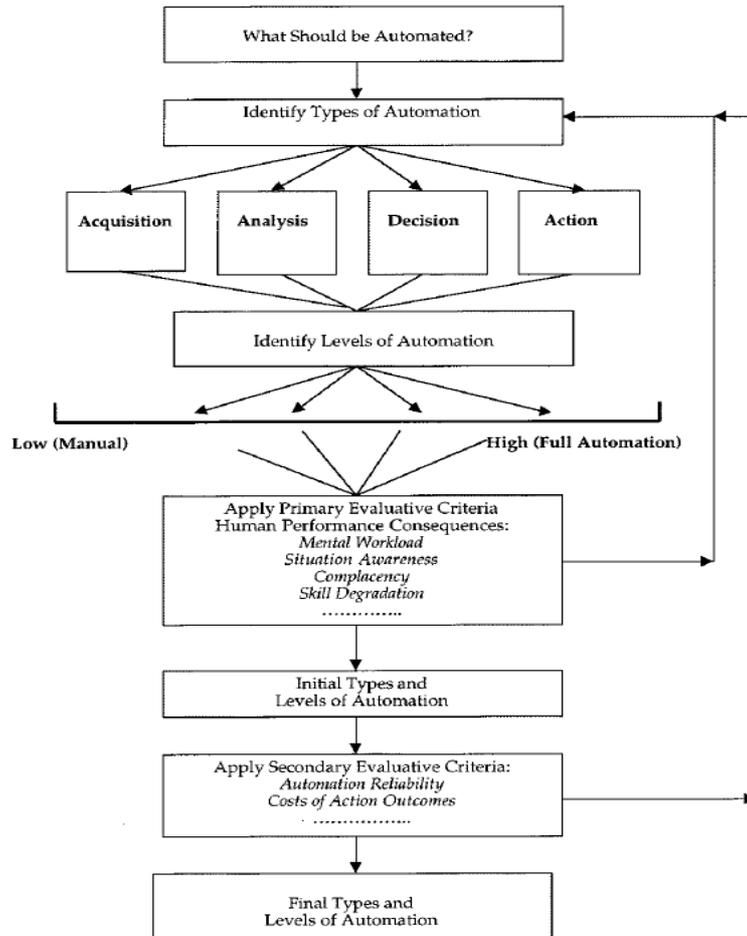


Figure 14: The methodology developed by Parasuraman [25]

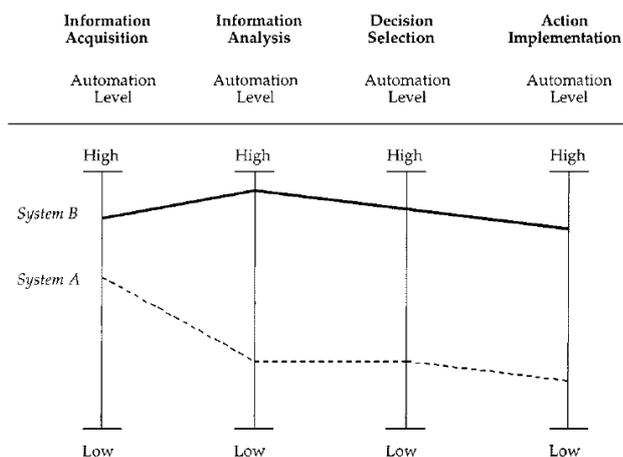


Figure 15: Levels of automation for the independent functions [25]

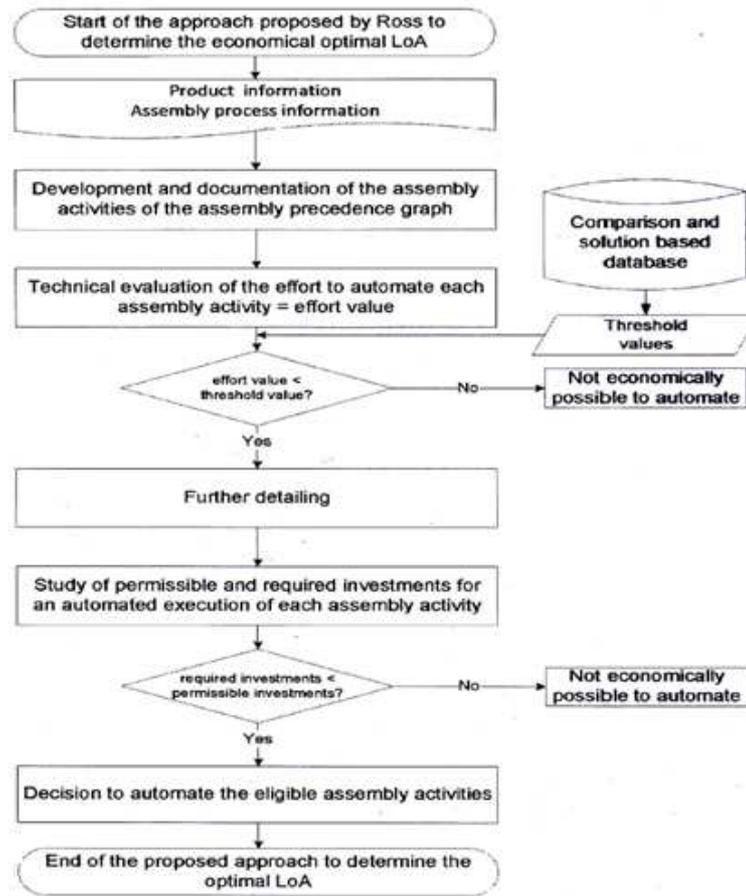


Figure 16: The methodology developed by Ross [93]

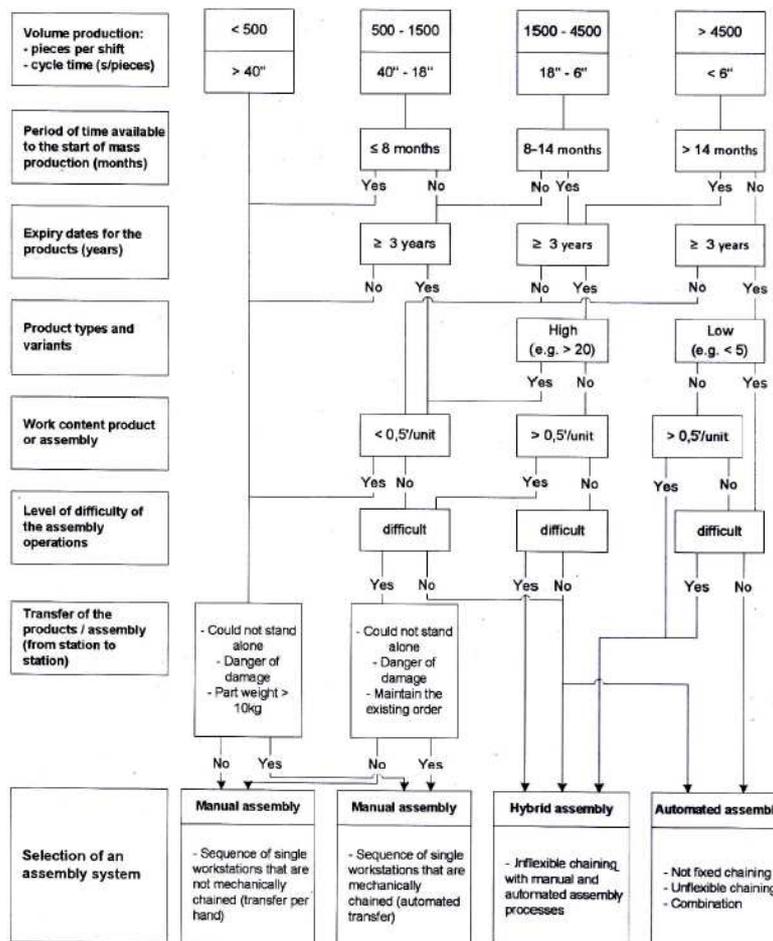


Figure 17: The methodology developed by Ross [93]

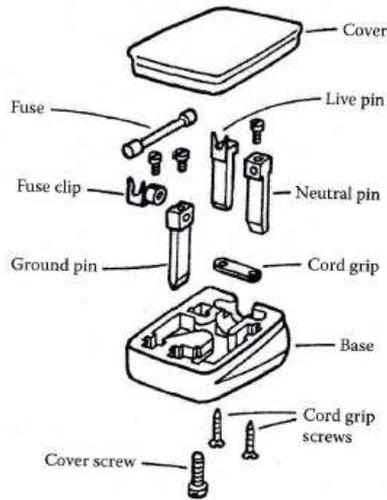


Figure 18: The power plug to assemble studied by Boothroyd for decision about automation issue [95]

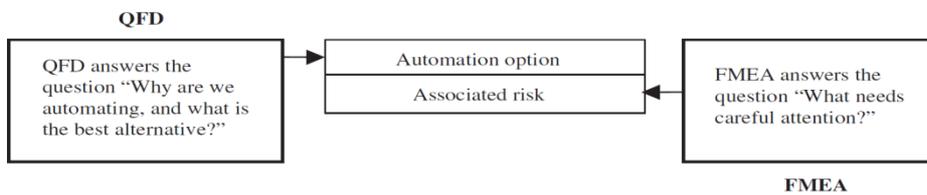


Figure 19: The manufacturing automation decision tool concept developed by Almannai [59]



Figure 20: The decision making framework built by Almannai [59]

1. Plan ahead before the measurement
2. On site, start with a pre-study to identify the process
3. Visualize and document the production flow
4. Identify the main task for each section/cell
5. Identify sub-tasks for each section/cell
6. Measure LoA
7. Asses LoA, set relevant max. and min. levels
8. Analysis of results

Figure 21: The Dynamo methodology in eight steps [12,13]

LoA _{mech}	Task 11.1	Task 11.2	Task 11.3	Task 11.4	Task 11.5	LoA _{info}	Task 11.1	Task 11.2	Task 11.3	Task 11.4	Task 11.5
7						7					
6		Max				6		Max	Max	Max	
5	Max			Max	Max	5		Max			
4			Min			4	Max				Max
3						3		Min			
2						2					
1	Min	Min		Min	Min	1	Min	Min	Min	Min	Min

Figure 22: Workshop to decide min and max LoA values in a case study [10]

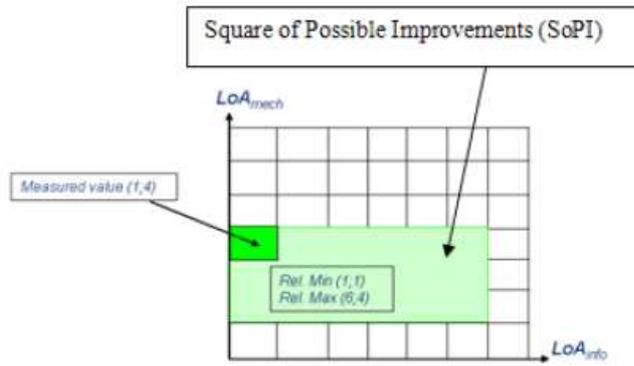


Figure 23: The LoA matrix : application of a case study [10]

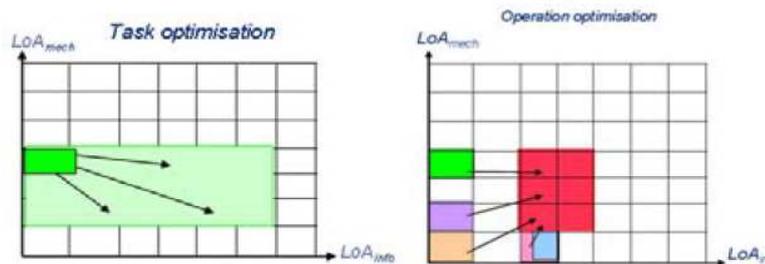


Figure 24: Task and operation optimization [10]

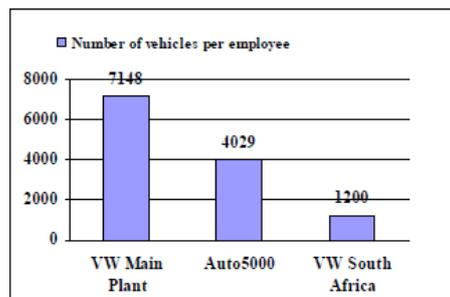


Figure 25: Annual vehicle quantity per employee in the 3 studied sites [38]

Table 7: The MABA-MABA list [53]

Men are better at	Machines are better at
Detecting small amounts of visual, auditory, or chemical energy	Responding quickly to control signals
Perceiving patterns of light or sound	Applying great force smoothly and precisely
Improvising and using flexible procedures	Storing information briefly, erasing it completely
Storing information for long periods of time and recalling appropriate parts	Reasoning deductively
Reasoning inductively	
Exercising judgment	

Table 8: The studied companies case studies in automation issue [23]

Case	Industry	Size of company/site (no of employees)	Product: size, volume, complexity	Year of study
Case A	Telecom	1500	Small, very high volume, complex	2000
Case B	Automotive	650	Large, medium volume, complex	1998
Case C	Wood	400	Medium, medium, medium	2004
Case D	Mechanical	400	Small, high volume, simple	2004
Case E	Furniture	<100	Medium, medium, medium	2006

Table 9: Processes comparison summary table [55]

	Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Name of type of automation approach	Semi-automated	Automated system dedicated to a single assay	Industrial automation with HTS technologies	Fully automated centralised robotic platform	Analytics: LC-MS with automated data handling
Name of specific technologies with associated companies	Tecan, Packard, Hamilton (http://www.hamiltoncompany.com/)	Sirius, Tecan, Hamilton, Zymark (http://www.zymark.com/) Beckman Coulter	Pharma companies, Cyprotex, TAP, EvotecOAI & Velocity 11 (http://www.velocity11.com/)	Pharma companies, Cyprotex, The Automation Partnership, Hamilton & Zymark	Applied Biosystems/MDS, Sciex, Micro-mass, custom solutions from Pharma
Pros	<ul style="list-style-type: none"> • Redundancy and flexibility • Adaptable approach to available budget 	<ul style="list-style-type: none"> • Individual workstations dedicated to an assay • Gold standard measurements 	<ul style="list-style-type: none"> • Use of leading-edge robotic instrumentation • Maximum data in early discovery • Parallel operation 	<ul style="list-style-type: none"> • Flexibility to perform multiple tasks • Unattended operation • Saving on staff resources • Flexibility 	<ul style="list-style-type: none"> • Specificity • Multi-analyte detection • Robust to ADME samples • Multi-plexing and sample pooling
Cons	<ul style="list-style-type: none"> • Limited throughput • Intensive use of manual resources 	<ul style="list-style-type: none"> • Less flexibility to perform other assays on the dedicated instruments 	<ul style="list-style-type: none"> • Less flexible to change • Poorer data quality 	<ul style="list-style-type: none"> • Detailed programming and scheduling • Long development times 	<ul style="list-style-type: none"> • Single approach • Slow cf. plate-readers • Instruments quickly outdated
Capacity and Costs	<ul style="list-style-type: none"> • Lower capacity • Cost-effective, manually intensive 	<ul style="list-style-type: none"> • Capacity limited for screening • Mid- to low-cost 	<ul style="list-style-type: none"> • HTS-like capacity and speed • High capital investment required 	<ul style="list-style-type: none"> • High capacity • High initial capital and infrastructure investment 	<ul style="list-style-type: none"> • High capacity • Instruments expensive to purchase and operate

Table 10: The experience of some manufactories with automation (built from [23])

The Strategy and Context of the manufacturer	Results of the experience
<u>Manufacturer A</u>	
<p>Decisions were made on automation of the final assembly line for cellular phones. The order from top management was to automate as much as possible. The company lacked competence and experiences from automated assembly systems</p>	<p>Failure The problems associated with the new automated assembly line were neglected by the management, which contributed to the poor outcome and the following drastic cost reductions.</p>
<u>Manufacturer B</u>	
<p>The automation strategy was not linked to the company's manufacturing capabilities, the company in one of its plants introduced industrial robots and new sophisticated equipment in order to improve flexibility, increase productivity, and reduce manufacturing cost.</p>	<p>Failure The equipment was, too complicated and problems occurred After a few years, the company removed the robots and went back to more manual tasks, which led to an increase in productivity by 50%</p>
<u>Manufacturer C</u>	
<p>The company C made a comparatively large investment in a new production line. The production line is designed in two sections, the first half is fully automated and the second is entirely manual. the company's policy is to be very flexible, and meet the customers' demands on more or less customized products</p>	<p>Failure Enormous problems occur in balancing the manual part of the line since the work content varies Huge buffers, which increase the cost for work in process, are built up and have to be taken care of, thus causing extra cost. the investment was not correlated to the long-term business and manufacturing strategies The lack of competence in handling automated equipment is also a problem.</p>
<u>Manufacturer D</u>	
<p>Automation decisions are made in congruence with the other decisions in a manufacturing strategy The present plant (built automated) is fairly new since the old one was destroyed by fire in year 1996. The main key to success, in the company's opinion, has been a combination of good industrial engineering and business development Important success factors are considered to be in-house product development and good control of the manufacturing process Their competitive priorities are short development time, flexibility, and reliable deliveries. The start of the new factory was in fact an opportunity to create something really well planned.</p>	<p>Success The result was that the plant was organized in four different production flows, which are well suited for each category of products. The delivery precision and reliability have improved considerably compared with the old plant. Reduced lead-time, from 4 to 5 weeks to 10 days The productivity has more than tripled The capacity doubled The production area has been reduced to half.</p>
<u>Manufacturer E</u>	
<p>The company experienced a crisis since their larger competitors showed much higher productivity than this small (22 employees) independent manufacturer The manufacturing showed a very low level of automation and about 90% of the manufacturing cost emanated from cost of labour and only 10% from depreciation of investments. Most equipment was general purpose, which demanded a high manning level. The premium segment of office furniture (domain of this company E) demands high quality and a high degree of customized design. The manufacturing equipment was quite old and could not cope with the output demands and it was not possible to meet the customization requirements. The company decided to invest in state-of-the-art equipment.</p>	<p>Success They have seen to training the operators in the new machines, even if the operators sometimes were quite old and had a rather short time to retirement. Today the level of education is comparatively high and all employees have at least 2–3 years of professional education and some have university degrees. The operators do their own CAM (Computer aided manufacturing) conversion of the drawing data at the office and data is transferred on-line to the machines. Their main competitive priorities are:</p> <ul style="list-style-type: none"> - Design adaptation. - Flexibility and customization. - Cost. - Efficiency and productivity. - Lead times and delivery precision.

Table 11: Different parameters shown as a function of the LoA x_{af} [28]

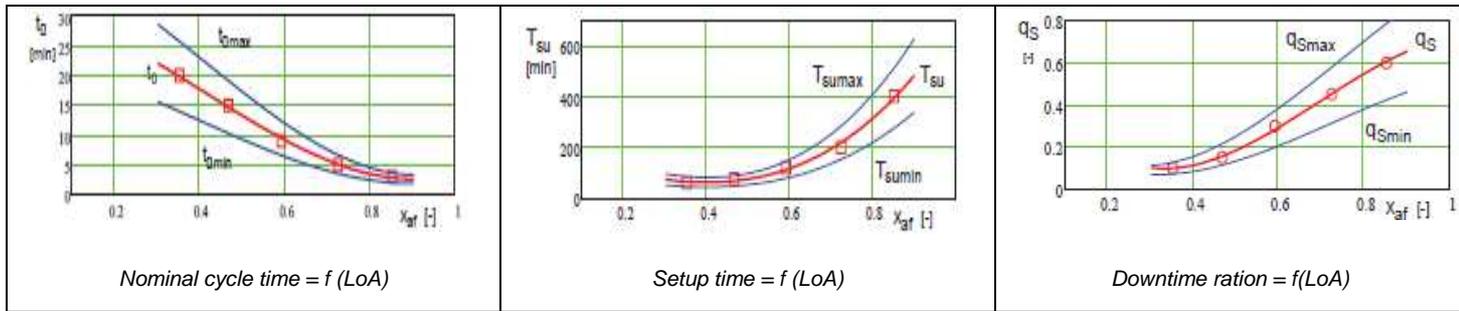


Table 12: Part cost and production capacity as function of the level of automation factor x_{af} for each of the production systems A-F [28]

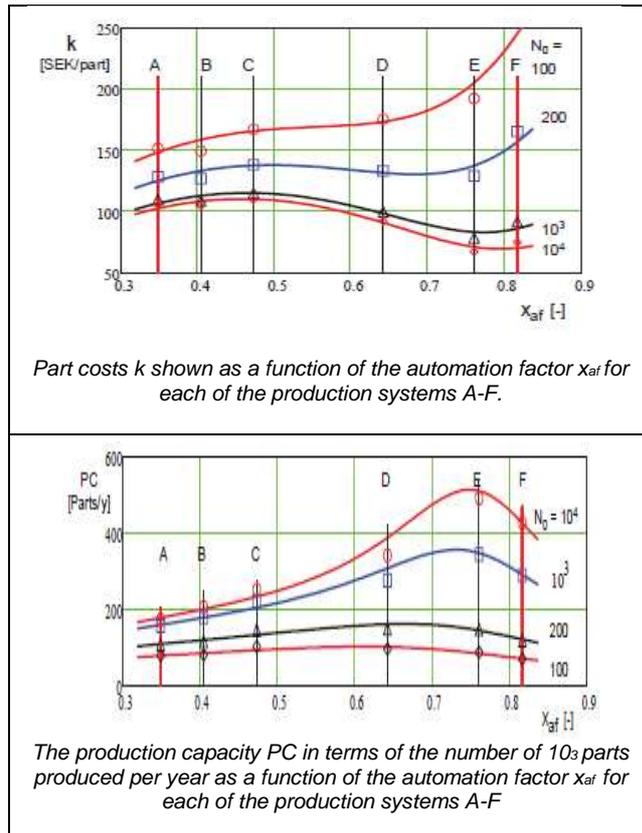


Table 13: Actual and recommended (optimal) levels of automation [38]

Index	Golf A5 Wolfsburg			Touran at Auto5000 Wolfsburg			Golf A5 Uitenhage		
	Optimal Level of Automation of Assembly Parts								
	AP1	AP2	AP3	AP1	AP2	AP3	AP1	AP2	AP3
Cost	1	4	4	3	4	4	5	5	7
Quality	3	4	4	3	4	1	3	4	1
Productivity/Flexibility	1	2	4	2	3	4	4	4	6
Present Automation Level	1	1	1	4	4	4	5	5	7
Recommended Automation Level	1	4	4	3	4	3	5	5	7

APX : Assembly Part X

Table 14: Comparison of results of product cost for the different assembly systems [95]

		Multistation Special-Purpose			Robot Systems		
		Manual Assembly	Indexing	Free-Transfer	1-Arm	2-Arm	Multistation
Number of systems:		6	1	1	3	2	1
Number of stations:	Manual	1	2	2	0	0	0
	Auto	—	6	6	0	0	1
	Robot	—	—	—	1	1	4
Total	Assembly	6	2	2	0	0	0
system workers	Tech	—	1	1	1	1	1
Total equipment costs ^a		—	194	348	462	448	547
Assembly rate/min		8.4	5.7	6.7	7.3	9.5	7.7
Assembly costs, cents		45.0	48.6	49.3	43.4	41.8	45.4

Table 15: Unit cost of the assembly of vehicles in the 3 studied sites [38]

Level of Automation	Assembly Part 1, €	Assembly Part 2, €	Assembly Part 3, €
1	1,00	1,20	1,20
2	1,10	1,30	1,10
3	1,20	1,10	1,10
4	1,30	1,00	1,00
5	1,40	1,40	1,30
6			1,40
7			1,50

Level of Automation	Assembly Part 1, €	Assembly Part 2, €	Assembly Part 3, €
1	1,30	1,20	1,30
2	1,20	1,30	1,20
3	1,00	1,10	1,10
4	1,10	1,00	1,00
5	1,40	1,40	1,40
6			1,50
7			1,60

Level of Automation	Assembly Part 1, €	Assembly Part 2, €	Assembly Part 3, €
1	1,40	1,40	1,60
2	1,30	1,30	1,50
3	1,20	1,20	1,30
4	1,10	1,10	1,20
5	1,00	1,00	1,10
6			1,40
7			1,00

<i>Unit cost of the assembly of the Golf A5 model produced in Wolfsburg (Germany)</i>	<i>Unit cost of the assembly of the Touran model produced in Auto5000 site (Germany)</i>	<i>Unit cost of the assembly of the Golf A5 model produced in Uitenhage (South Africa)</i>
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Table 16: Quality indices [38]

Plant	Trouble cases per unit			Field Data (Trouble cases per unit)	Audit Points (Target)	VPC Data (Trouble cases per unit)	DRR CP7/CP8, %	Process Audit, %
	Assembly Part 1	Assembly Part 2	Assembly Part 3					
Main Plant in Wolfsburg	0,01345	0,02796	0,00465	0,05432	80(90)	2,44	58/62	94
Auto5000 in Wolfsburg	0,03872	0,01235	0,01987	0,01076	82(90)	0,87	69/95	91
Plant in South Africa	0,10984	0,03561	0,96543	0,02345	92(90)	2,23	81/89	92

*VPC : Vehicle Preparation Center,
*DRR : Direct Runner Rate

Table 17: Optimal Levels of automation with regard to flexibility [38]

Golf A5 Wolfsburg																	
Level	Number of workers																
	Assembly Part 1					Assembly Part 2					Assembly Part 3						
Units	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	6	7
-20%	8	10	14	19	19	7	10	10	9	34	6	6	8	8	13	15	18
Actual	9	11	14	19	22	8	10	11	12	42	6	8	8	8	13	17	20
+20%	10	13	18	25	28	9	12	14	14	48	6	8	10	8	14	18	23

Auto 5000 Wolfsburg																	
Level	Number of workers																
	Assembly Part 1					Assembly Part 2					Assembly Part 3						
Units	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	6	7
-20%	8	10	13	18	18	7	10	10	9	32	6	6	8	8	12	15	18
Actual	9	11	14	19	21	8	10	10	10	39	6	8	8	8	13	17	20
+20%	10	12	15	23	25	9	11	11	11	45	6	8	8	8	14	18	23

Golf A5 SA																	
Level	Number of workers																
	Assembly Part 1					Assembly Part 2					Assembly Part 3						
Units	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	6	7
-20%	4	6	8	10	8	4	6	8	7	11	4	5	7	7	9	9	9
Actual	5	6	8	10	9	4	6	8	7	12	4	5	7	7	9	9	9
+20%	5	6	8	10	9	4	6	8	7	14	4	5	7	7	9	9	10

Table 18: Optimal levels of automation [38]

Index	Golf A5 Wolfsburg			Touran at Auto5000 Wolfsburg			Golf A5 Uitenhage		
	Optimal Level of Automation of Assembly Parts								
	AP1	AP2	AP3	AP1	AP2	AP3	AP1	AP2	AP3
Cost	1	4	4	3	4	4	5	5	7
Quality	3	4	4	3	4	1	3	4	1
Productivity/Flexibility	1	2	4	2	3	4	4	4	6
Present Automation Level	1	1	1	4	4	4	5	5	7
Recommended Automation Level	1	4	4	3	4	3	5	5	7

Appendix 5: Literature Graphical Representation Methods usable for assembly

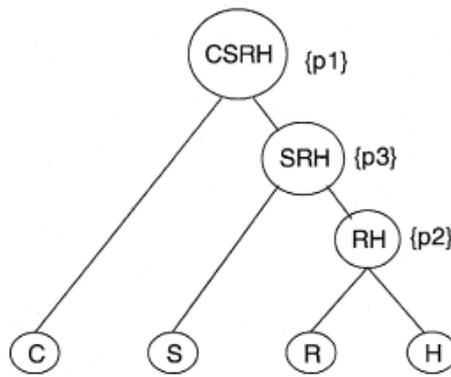


Figure 26: scencegraph structure for an example in assembly [106]

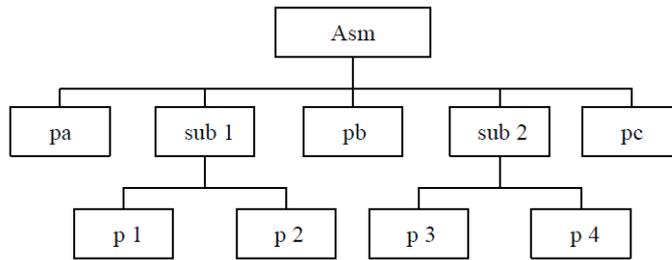


Figure 27: Hierarchical structure model for an example in assembly [108]

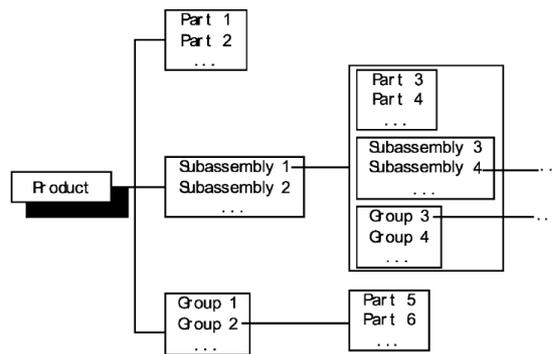


Figure 28: Hierarchical structure of a product example in assembly [109]

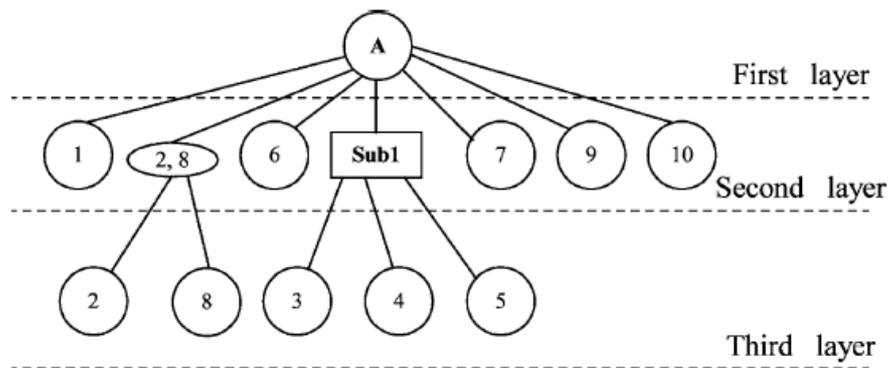


Figure 29: Hierarchical Relation Graph of a product example in assembly [109]

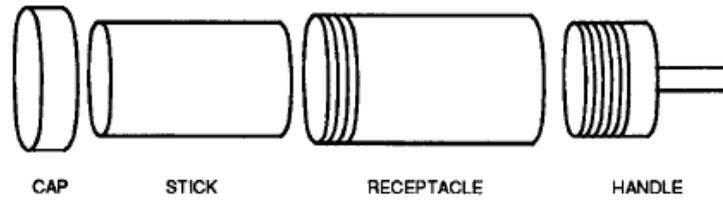


Figure 30: A product example to assemble [112]

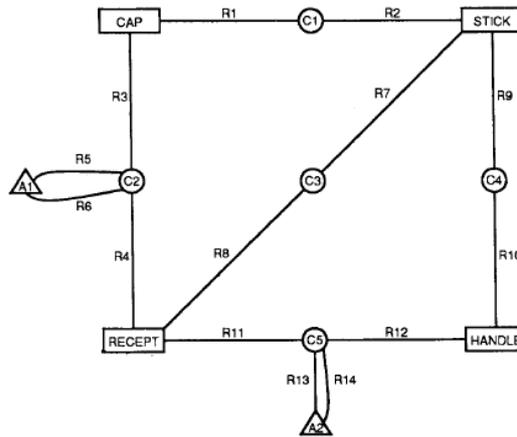


Figure 31: Relational model for the product assembly example shown in figure 30 Appendix [113]

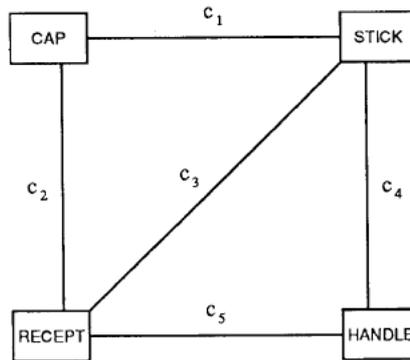


Figure 32: Graph of connections for product assembly example shown in figure 30 Appendix [113]

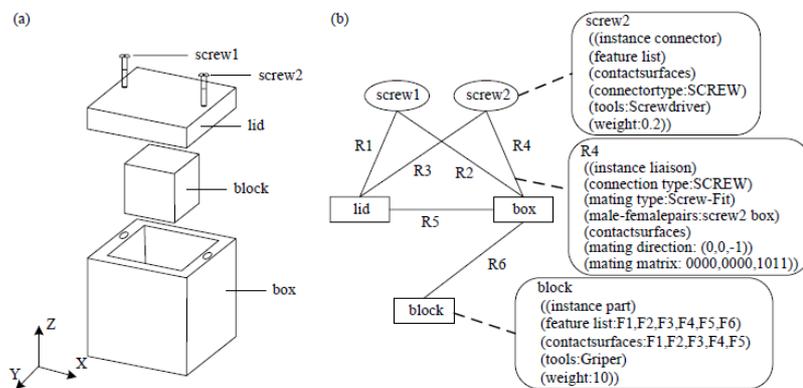


Figure 33: CSBARM model for a product assembly example [108]

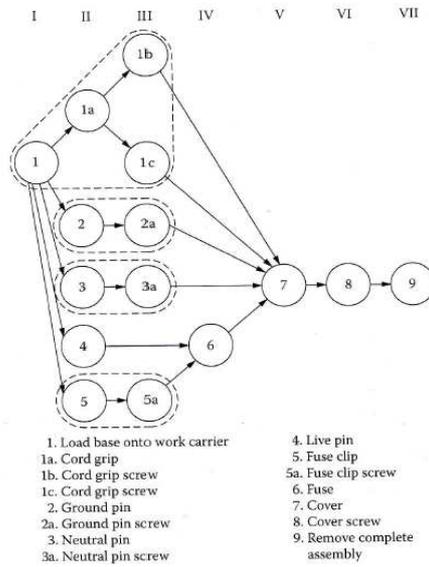


Figure 34: Example of precedence graph of the product assembly shown in figure 18 [95]

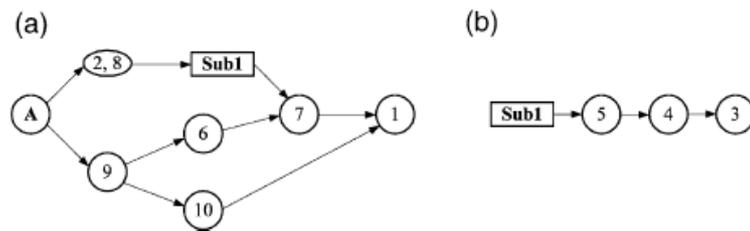


Figure 35: Precedence graph for an example and the use of procedures [109]

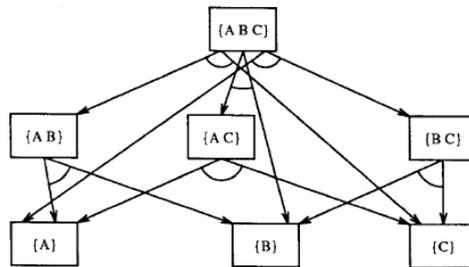


Figure 36: the AND/OR Graph representation principle [113]

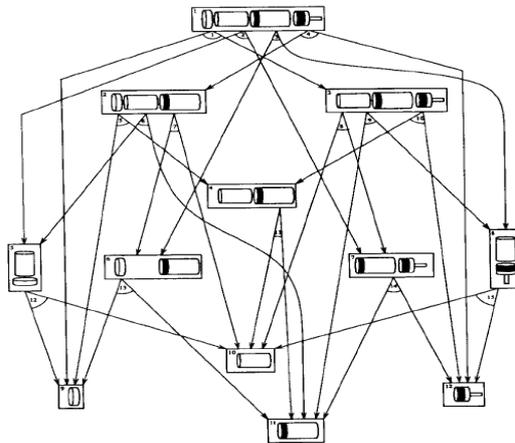


Figure 37: AND/OR graph of feasible assembly sequences for the product assembly example shown in figure 30 Appendix [112]

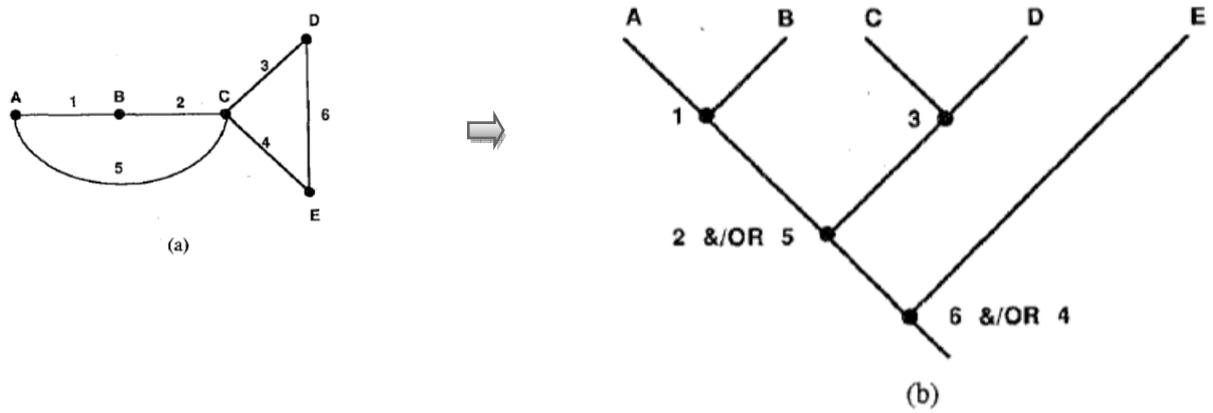


Figure 38: Parts tree representation corresponding to a given liaison diagram for a product assembly example [111]

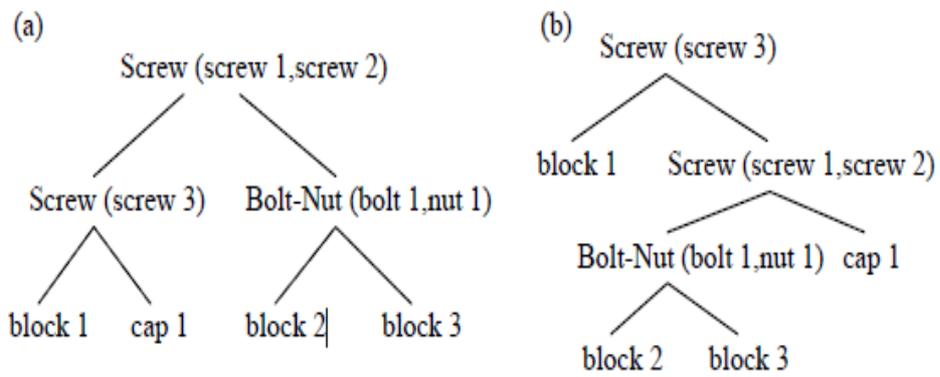


Figure 39: CSBAT models for a product assembly example [108]

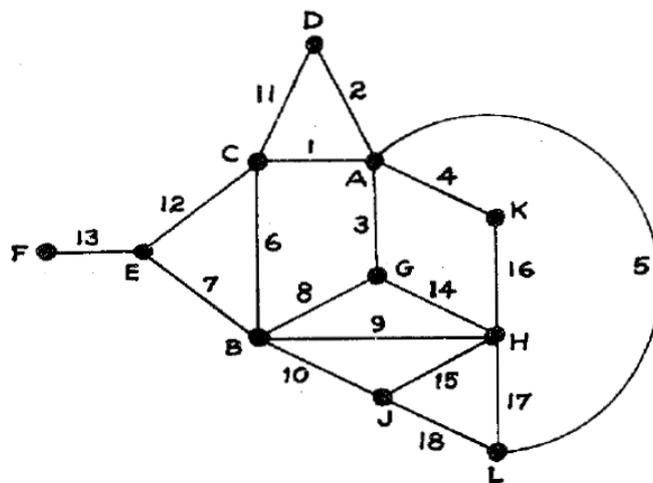


Figure 40: Liaison diagram of a product example in assembly [111]

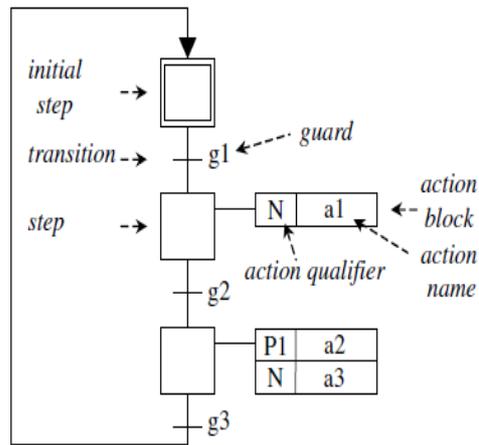


Figure 41: Elements of SFC [115]

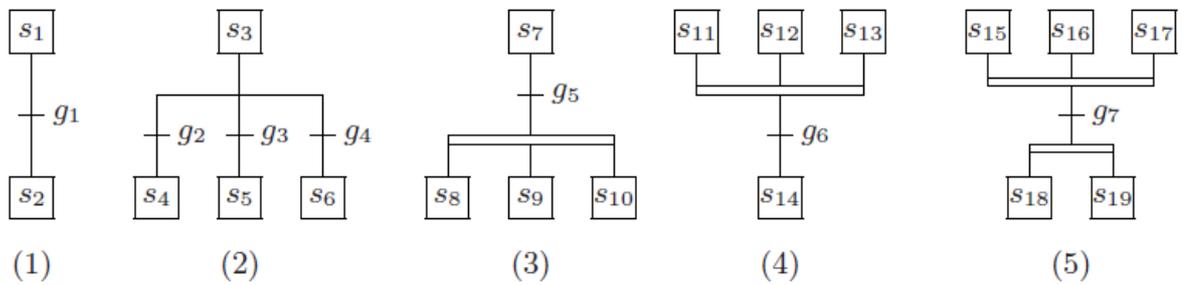


Figure 42: Reference types in SFC modeling language [115]

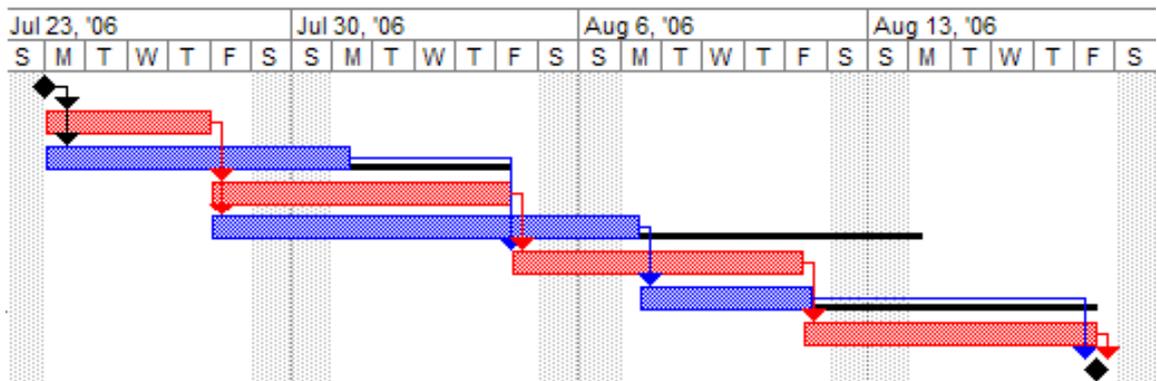


Figure 43: The GANTT modeling language applied on an example [116]

Appendix 6: Time standards in the Literature

MANUAL HANDLING-ESTIMATED TIMES (s)

Key:			Parts are easy to grasp and manipulate					Parts present handling difficulties (1)										
			Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm							
			Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm						
□	□	□	0	1	2	3	4	5	6	7	8	9						
Parts can be grasped and manipulated by one hand without the aid of grasping tools	□	One hand	$(\alpha+\beta) < 360^\circ$	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98				
			$360^\circ \leq (\alpha+\beta) < 540^\circ$	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38				
			$540^\circ \leq (\alpha+\beta) < 720^\circ$	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7				
			$(\alpha+\beta) = 720^\circ$	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4				
Parts can be grasped and manipulated by one hand but only with the use of grasping tools	□	One hand with grasping aids	Parts need tweezers for grasping and manipulation	Parts can be manipulated without optical magnification				Parts require optical magnification for manipulation				Parts need standard tools other than tweezers	Parts need special tools for grasping and manipulation					
				Parts are easy to grasp and manipulate		Parts present handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present handling difficulties (1)								
			Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	Thickness >0.25 mm	Thickness ≤0.25 mm	8	9				
			0	1	2	3	4	5	6	7	8	9	7	7				
			4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7					
			5	4	7.25	4.75	8	6	8.75	6.75	9	8	8					
			6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9					
			7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10					
			Parts can be grasped and manipulated by one hand but only with the use of grasping tools	□	One hand with grasping aids	$\alpha \leq 180^\circ$	$0 \leq \beta \leq 180^\circ$	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
							$\beta = 360^\circ$	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
$\alpha = 360^\circ$	$\alpha \leq \beta \leq 180^\circ$	6				4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9			
	$\beta = 360^\circ$	7				5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10			
Parts present no additional handling difficulties	□	Two hands for manipulation	$\alpha \leq 180^\circ$	Parts present no additional handling difficulties		Parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)												
						$\alpha = 360^\circ$		$\alpha \leq 180^\circ$		$\alpha = 360^\circ$								
			Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm						
			0	1	2	3	4	5	6	7	8	9						
8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7								
Parts can be handled by one person without mechanical assistance	□	Two hands or assistance required for large size	Parts do not severely nest or tangle and are not flexible	Part weight < 10 lb				Parts are heavy (>10 lb)				Parts severely nest or tangle or are flexible (2)	Two persons or mechanical assistance required for parts manipulation					
				Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)		Parts are easy to grasp and manipulate		Parts present other handling difficulties (1)								
			$\alpha \leq 180^\circ$	$\alpha = 360^\circ$	$\alpha \leq 180^\circ$	$\alpha = 360^\circ$	$\alpha \leq 180^\circ$	$\alpha = 360^\circ$	$\alpha \leq 180^\circ$	$\alpha = 360^\circ$	$\alpha \leq 180^\circ$	$\alpha = 360^\circ$	8	9				
			0	1	2	3	4	5	6	7	8	9						
			9	2	3	2	3	3	4	4	5	7	9					

Notes:

- Parts can present handling difficulties if they nest or tangle, stick together because of magnetic force or grease coating, and so on, are slippery, or require careful handling. Parts that nest or tangle are those that interlock when in bulk but can be separated by one simple manipulation of a single part, for example, taper cups, closed-end helical springs, circlips, and so on. Parts that are slippery are those that easily slip from fingers or standard grasping tool because of their shape and/or surface condition. Parts that require careful handling are those that are fragile or delicate, have sharp corners or edges, or present other hazards to the operator.
- Parts that nest or tangle severely are those parts that interlock when in bulk and both hands are needed to apply a separation force or achieve specific orientation of inter-locking parts to achieve separation. Flexible parts are those that substantially deform during manipulation and necessitate the use of two hands. Examples of such parts are large paper or felt gaskets, rubber bands or belts, and so on.

Figure 44: Classification system for part features affecting manual handling time

MANUAL INSERTION-ESTIMATED TIMES (s)

		After assembly no holding down required to maintain orientation and location (3)				Holding down required during subsequent processes to maintain orientation at location (3)					
		Easy to align and position during assembly (4)		Not easy to align or position during assembly		Easy to align and position during assembly (4)		Not easy to align or position during assembly			
		No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)		
		0	1	2	3	6	7	8	9		
Addition of any part (1) where neither the part itself nor any other part is finally secured immediately Part and associated tool (including hands) can easily reach the desired location		0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5	
	Due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10	
	Due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5	
Addition of any part (1) where the part itself and/or other parts are being finally secured immediately Part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily		No screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		Plastic deformation immediately after insertion				Screw tightening immediately after insertion			
	Due to obstructed access or restricted vision (2)	Easy to align and position with no resistance to insertion (4) Not easy to align or position during assembly and/or resistance to insertion (5)	Easy to align and position during assembly (4)	Plastic bending or torsion		Riveting or similar operation		Easy to align and position with no torsional resistance (4) Not easy to align or position during assembly	Not easy to align or position and/or torsional resistance (5)		
	Due to obstructed access and restricted vision (2)			No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)				
	0	1	2	3	4	5	6	7	8	9	
Addition of any part (1) where the part itself and/or other parts are being finally secured immediately Part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily		3	2	5	4	5	6	7	8	9	
	Due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	
	Due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	
Assembly processes where all solid parts are in place		Mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)			Non-fastening processes		
	None or localized plastic deformation	Bending or similar processes	Riveting or similar processes	Screw tightening or other processes	Bulk plastic deformation (large proportion of part is plastically deformed during fastening)	Metallurgical processes		Chemical processes (e.g. adhesive bonding, etc.)	Manipulation of parts or sub-assembly (e.g. orienting, fittings or adjustment of parts, etc.)	Other processes (e.g. liquid insertion, etc.)	
						No additional material required (e.g. resistance, friction welding, etc.)	Additional material required				
	0	1	2	3	4	5	6	7	8	8	
	9	4	7	5	12	7	8	12	12	9	12

Key:
 Part added but not secured

Part secured immediately

Separate operation

Notes:

1. A part is the solid or nonsolid element of an assembly during an assembly process. A subassembly is considered a part if it is added during assembly. However, adhesives, fluxes, fillers, and so on, used for joining parts are not considered to be parts.
2. Obstructed access means that the space available for the assembly operation causes a significant increase in the assembly time. Restricted vision means that the operator has to rely mainly on tactile sensing during the assembly process.
3. Holding down required means that the part is unstable after placement or insertion or during subsequent operations and will require gripping, realignment, or holding down before it is finally secured. Holding down refers to an operation that, if necessary, maintains the position and orientation of a part already in place, prior to, or during the next assembly operation. A part is located if it will not require holding down or realignment for subsequent operations and is only partially secured.
4. A part is easy to align and position if the position of the part is established by locating features on the part or on its mating part and insertion is facilitated by well designed chamfers or similar features.
5. The resistance encountered during part insertion can be due to small clearances, jamming or wedging, hang-up conditions, or insertion against a large force. For example, a press fit is an interference fit where a large force is required for assembly. The resistance encountered with self-tapping screws is similarly an example of insertion resistance.

Figure 45: Classification system for part features affecting manual insertion time

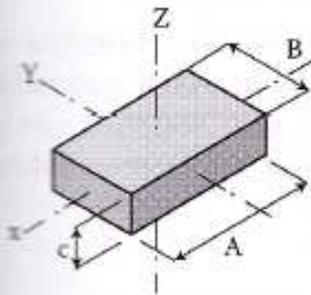
AUTOMATIC HANDLING-DATA FOR ROTATIONAL PARTS																
(first digit 0, 1 or 2)																
Part is symmetrical about its principal axis (BETA symmetric) (see note 2)	Part is not BETA symmetric (code the main feature or features requiring orientation about the principal axis)															
	BETA asymmetric projections, steps, or chamfers (can be seen in silhouette)						BETA asymmetric grooves or flats (can be seen in silhouette)				Slightly asymmetric or small features less than D/10 and L/10 or holes or recesses which cannot be seen in outer shape of silhouette					
	On side surface only	On end surface(s) only	On both side and end surface(s)		Through groove or flat can be seen in end view	Through groove can be seen in side view										
0	2	3	4	5	6	7	8									
Part is ALPHA symmetric (see note 1)	Part is not ALPHA symmetric (code the main feature or features requiring end-to-end orientation) (see note 1)															
	Part can be fed in a slot supported by large end or protruding flange	1	0.7	1	0.3	1	0.5	1	0.3	1	0.35	1	0.2	1	0.5	1
			0.7	1	0.15	1	0.2	1	0.15	1	0.2	1	0.2	1	0.2	1
			0.9	1	0.45	1	0.9	2	0.45	1	0.9	1	0.9	2	0.9	2
	BETA symmetric steps or chamfers on external surfaces (see note 3)	2	0.4	1	0.2	1	0.25	1	0.2	1	0.2	1	0.1	1	0.25	1
			0.3	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1	0.1	1
			0.9	1	0.45	1	0.9	2	0.45	1	0.9	1	0.9	2	0.9	1
	BETA symmetric grooves holes or recesses (see note 3)	3	0.4	1	0.15	1	0.25	1	0.15	1	0.35	1	0.1	1	0.25	1
			0.3	1	0.1	1.5	0.1	1.5	0.1	1.5	0.2	1.5	0.05	1.5	0.1	1.5
		4	0.75	1	0.37	1.5	0.25	3	0.37	2.5	0.5	1	0.5	3	0.5	2
			0.5	1	0.15	1	0.25	1	0.15	1	0.2	1	0.1	3	0.25	1
		5	0.2	1	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.05	1.5	0.1	1.5
0.85			1	0.48	1.5	0.25	2	0.43	1.5	0.5	1	0.5	2	0.5	2	
6	0.5	1	0.15	1	0.25	1	0.15	1	0.2	1	0.1	1	0.25	1		
	0.2	1	0.1	1.5	0.1	1.5	0.1	1.5	0.1	1.5	0.05	1.5	0.1	1.5		
7	0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.15	1	0.45	2	0.45	2		
	0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.45	1	0.45	2	0.45	2		
8	0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.45	1	0.45	2	0.45	2		
	0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.45	1	0.45	2	0.45	2		
8	0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.45	1	0.45	2	0.45	2		
	0.6	1	0.27	1.5	0.25	2	0.27	1.5	0.45	1	0.45	2	0.45	2		
MANUAL HANDLING REQUIRED																

Notes:

1. A rotational part is alpha symmetric if it does not require orienting end-to-end. If a part can only be inserted into the assembly in one direction then it is referred to as "not alpha symmetric."
2. A beta-symmetric part has rotational symmetry and therefore does not require orienting about its principal axis.
3. A beta-symmetric step, chamfer or groove is a concentric reduction or increase in diameter; its cross section can be circular or any regular polygon. Less significant features should be ignored.
4. Parts in this category have an alpha-symmetric external shape, but the internal surface (composed perhaps of cavities, counterbores, grooves, etc.) requires that the part be oriented end to end.

Figure 46: Geometrical classification for rotational parts

AUTOMATIC HANDLING-DATA FOR NON-ROTATIONAL PARTS (first digit 6, 7 or 8)																		
A ≤ 1.1B or B ≤ 1.1C (Code the main feature or features which distinguish the adjacent surfaces having similar dimensions)																		
KEY E C _r																		
Steps or chamfers (2) parallel to- Through grooves (2) parallel to-																		
X axis and > 0.1C Y axis and > 0.1C Z axis and > 0.1B X axis and > 0.1C Y axis and > 0.1C Z axis and > 0.1B Holes for recesses > 0.1B (cannot be seen in silhouette) Other including slight asymmetry (3), features too small etc																		
0 1 2 3 4 5 6 7 8																		
Part has 180° symmetry about all three axes (1)	0	0.8	1	0.8	1	0.2	1	0.5	1	0.75	1	0.25	1	0.5	1.6	0.25	2	Manual handling required
		0.9	1	0.9	1	0.5	2	0.5	1.5	0.5	1	0.5	1.5	0.6	1	0.5	1	
		0.6	1	0.5	1	0.15	2	0.15	1.5	0.5	1	0.15	1	0.15	1.5	0.15	2	



Code the main feature or if orientation is defined by more than one feature, then code the feature that gives the largest third digit																	
Steps or chamfers (2) parallel to- Through grooves (2) parallel to-																	
X axis and > 0.1C Y axis and > 0.1C Z axis and > 0.1B X axis and > 0.1C Y axis and > 0.1C Z axis and > 0.1B Holes for recesses > 0.1B (cannot be seen in silhouette) Other including slight asymmetry (3), features too small etc																	
0 1 2 3 4 5 6 7																	
Part has 180° symmetry about one axis only (1)	About X axis	1	0.4	1	0.6	1	0.4	1.5	0.4	1	0.3	1	0.7	1	0.4	2	MANUAL HANDLING REQUIRED
			0.5	1	0.15	1	0.25	2	0.5	1	0.25	1	0.25	1.5	0.25	3	
			0.4	1	0.6	1	0.4	2	0.2	1	0.3	1	0.15	1	0.1	2	
About Y axis	2	0.4	1	0.3	1	0.4	1.5	0.5	1	0.3	1	0.4	1	0.4	2		
		0.4	1	0.2	1	0.25	2	0.4	1	0.25	1	0.25	1	0.25	2		
		0.5	1	0.15	1	0.5	2	0.2	1	0.15	1	0.15	2	0.15	2		
About Z axis	3	0.4	1	0.3	1	0.4	1.5	0.4	1	0.3	1	0.1	1.5	0.4	2		
		0.3	1	0.2	1	0.25	2	0.3	1	0.25	1	0.25	2	0.25	2		
		0.4	1	0.2	1	0.4	2	0.2	1	0.15	1	0.15	2	0.15	2		
Part has no symmetry (code the main feature(s) that define the orientation) (4)	Orientation defined by one main feature	4	0.25	1	0.15	1	0.15	1.5	0.1	1	0.25	1	0.1	1.5	0.1	2	
			0.25	1	0.1	1.5	0.24	2	0.2	1	0.1	1.5	0.15	2	0.15	3	
			0.15	1	0.14	1	0.15	1	0.1	1	0.05	1	0.1	1.5	0.08	2	
	Orientation defined by two main features and one is a step, chamfer or groove	6	0.2	2	0.15	2	0.1	2.5	0.1	2	0.15	2	0.1	2.5	0.1	3	
		0.1	3	0.1	3.5	0.1	4	0.1	3	0.1	3.5	0.1	4	0.1	5		
		0.05	2	0.05	2	0.05	2.5	0.05	2	0.05	2	0.05	2.5	0.05	3		
Other including slight asymmetry (3) etc.	9	MANUAL HANDLING REQUIRED															

Notes:

1. A rotational symmetry of 180° about an axis means that the same orientation of the part will be repeated only once by rotating the part through 180° about that axis.
2. Steps, chamfers, or through grooves are features that can be seen in silhouette.
3. Exposed features are prominent but the asymmetry caused by these features is less than 0.1 of the appropriate envelope dimension. For a part that has 180° rotational symmetry about a certain axis, slight asymmetry implies that the part has almost 90° rotational symmetry about that axis.
4. A part having no rotational symmetry means that the same orientation of the part will not be repeated by rotating the part through any angle less than 360° about any one of the three axes X, Y, or Z.
A main feature is a feature that is chosen to define the orientation of the part. All the features that are chosen to completely define the orientation of the part should be necessary and sufficient for the purpose.
Often, features arise in pairs or groups and the pair or group of features is symmetric about one of the three axes X, Y, or Z. In this case, the pair or group of features should be regarded as one main feature. Using this convention, two main features at most are needed to completely define the orientation of a part.

Figure 47: Geometrical classification for non rotational parts

AUTOMATIC HANDLING-ADDITIONAL FEEDER COSTS

Figures to be added to C₁

			Parts will not tangle or nest				Tangle or nest but not severely				Severely tangle	Severely tangle	
			Not light		Light		Not light		Light				
			Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky	Not sticky	Sticky			
			0	1	2	3	4	5	6	7			
Parts are small and non-abrasive	Parts do not tend to overlap during feeding	Not delicate	Non-flexible	0	0	1	2	3	2	3	3	4	MANUAL HANDLING REQUIRED
		Not delicate	Flexible	1	2	3	4	5	4	5	5	6	
		Delicate	Non-flexible	2	1	2	3	4	3	4	4	5	
			Flexible	3	3	4	5	6	5	6	6	7	
	Parts tend to overlap during feeding	Not delicate	Non-flexible	4	2	3	3	4	4	5	4	5	
			Flexible	5	4	5	5	6	6	7	6	7	
		Delicate	Non-flexible	6	3	4	4	5	5	6	5	6	
			Flexible	7	5	6	6	7	7	8	7	8	

		Very small parts					Large parts				
		Rotational		Non-rotational			Rotational		Non-rotational		
		L/D ≤ 1.5	L/D > 1.5	A/B ≤ 3	A/B > 3	A/C ≤ 4	L/D ≤ 1.5	L/D > 1.5	A/B ≤ 3	A/B > 3	A/C ≤ 4
		0	1	2	3	4	5	6	7	8	9
Parts are very small or large but are nonabrasive	8	2	2	2	2	2	9	9	9	9	9

		Parts will not severely tangle or nest								Severely tangle or nest
		Small parts				Large parts		Very small parts		
		Orientation defined by geometric features		Orientation defined by non-geometric features		Orientation defined by geometric features	Orientation defined by non-geometric features	Orientation defined by geometric features	Orientation defined by non-geometric features	
		Non-flexible	Flexible	Do not overlap	Overlap					
Do not overlap	Overlap	Do not overlap	Overlap	5	6	7	8	9		
Abrasive parts	9	2	4	4				9	4	

Notes:

Flexible: A part is considered flexible if the part cannot maintain its shape under the action of automatic feeding so that orienting devices cannot function satisfactorily.

Delicate: A part is considered delicate if damage may occur during handling, either due to breakage caused by parts falling from orienting sections or tracks onto the hopper base, or due to wear caused by recirculation of parts in the hopper. When wear is the criterion, a part would be considered delicate if it could not recirculate in the hopper for 30 min and maintain the required tolerance.

Sticky: If a force, comparable to the weight of a nontangling or nonnesting part, is required to separate it from bulk, the part is considered sticky.

Light: A part is considered too light to be handled by conventional hopper feeders if the ratio of its weight to the volume of its envelope is less than 1.5 kN/m³.

Figure 48: Additional relative feeder costs for a selection of feeding difficulties

AUTOMATIC INSERTION - RELATIVE WORKHEAD COST, W_r

			After assembly no holding down required to maintain orientation and location (5)				Holding down required during subsequent process(es) to maintain orientation and location (5)						
			Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)		Easy to align and position (6)		Not easy to align or position (no features provided for the purpose)				
Key:	Part added but not secured		No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)	No resistance to insertion	Resistance to insertion (7)			
			0	1	2	3	6	7	8	9			
No final securing is taking place (2)	Straight line insertion	From vertically above	0	1	1.5	1.5	2.3	1.3	2	2	3		
		Not from vertically above (3)	1	1.2	1.6	1.6	2.5	1.6	2.1	2.1	3.3		
	Insertion not straight line motion (4)	2	2	3	3	4.6	2.7	4	4	6.1			
Addition of any part (1) where final securing is taking place	Straight line insertion	From vertically above	3	1.2	1.9	1.6	2.4	3.6	0.9	1.4	2.1	0.8	1.8
		Not from vertically above (3)	4	1.3	2.1	2.1	3.2	4.8	1	1.5	2.3	1.3	2
	Insertion not straight line motion (4)	5	2.4	3.8	3.2	4.8	7.2	1.8	2.8	4.2	3.6	3.6	
Assembly process where all solid parts in place or non-solids added or parts are manipulated	Mechanical fastening processes (parts already in place)		None or localized plastic deformation				Non-mechanical fastening processes (parts already in place)						
	Bending or similar processes	Rivetting or similar processes	Screwing or other processes	Snap fit, snap clip, press fit, etc.	Metallurgical processes				Chemical processes (adhesive bonding etc.)	Manipulation of parts or sub-assembly (orienting, fitting, adjustment etc.)	Other processes (liquid insertion etc.)		
					Additional material required								
0	1	2	3	4	5	6	7	8	9				
9	1.6	0.9	0.8	1.6	1.2	1.1	1.1	0.8	1.5				

Figure 49: Relative workhead costs W_r for a selection of automatic insertion situations

ROBOT ASSEMBLY DATA FOR A SINGLE-STATION ONE-ARM SYSTEM

AR TP
AG TG

TP - Relative affective basic operation time
AR - Relative robot cost
AG - Relative additional gripper or tool cost
TG - Relative time penalty for gripper or tool change

		Part can be gripped and inserted using standard gripper or gripper used for previous part								Part requires change to special gripper								
		No holding down				Part requires temporary holding or clamping				No holding down				Part requires temporary holding or clamping				
		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		Self-aligning		Not easy to align		
		0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	
Part added but not finally secured	Using motion along or about the vertical axis	0	1.0	1.0	1.0	1.07	1.0	1.0	1.0	1.07	1.0	1.0	1.0	1.07	1.0	1.0	1.0	1.07
		0	0	0	0	0	1.0	0	1.0	0	1.5	2.1	1.5	2.1	2.5	2.1	2.5	2.1
	Using motion along or about a non-vertical axis	1	1.5	1.0	1.5	1.07	1.5	1.0	1.5	1.07	1.5	1.0	1.5	1.07	1.5	1.0	1.5	1.0
		0	0	0	0	0	1.0	0	1.0	0	1.5	2.1	1.5	2.1	2.5	2.1	2.5	2.1
	Involving motion along or about more than one axis	2	1.5	1.8	1.5	1.9	1.5	1.8	1.5	1.9	1.5	1.8	1.5	1.9	1.5	1.8	1.5	1.9
		0	0	0	0	0	1.0	0	1.0	0	1.5	2.1	1.5	2.1	2.5	2.1	2.5	2.1

		Force or torque levels within robot capability																Special workhead operation		
		Part can be gripped and inserted using standard gripper or gripper used for previous part								Part requires change to special gripper										
		Snap or push fit		Push and twist or other simple manipulation		Snap or push fit or simple manipulation		Screw fastening or nut running		Self-aligning		Not easy to align		Self-aligning		Not easy to align				
		0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	Robot positions part		
Part added and secured immediately	Using motion along or about the vertical axis	3	1.0	1.0	1.0	1.07	1.0	1.15	1.0	1.2	1.0	1.0	1.0	1.07	1.0	1.25	1.0	1.3	1.0	1.0
		0	0	0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.0	2.1	
	Using motion along or about a non-vertical axis	4	1.5	1.0	1.5	1.07	1.5	1.15	1.5	1.2	1.5	1.0	1.5	1.07	1.5	1.25	1.5	1.3	1.5	2.0
		0	0	0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.0	2.1	
	Involving motion along or about more than one axis	5	1.5	1.8	1.5	1.9	1.5	2.0	1.5	2.1	1.5	1.8	1.5	1.9					1.5	2.8
		0	0	0	0	0	0	0	0	1.5	2.1	1.5	2.1					4.0	2.1	

		Operation can be carried out using standard gripper or gripper used for previous operation									Operation requires change to special gripper or tool									Special workhead operation							
		Snap or push fit			Push and twist or simple manipulation			Reorient or unload assembly			Snap or push fit			Screw or nut tighten			Solder					Apply liquid or adhesive			Reorient or unload assembly		
		0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2			0	1	2	0	1	2
Separate securing operation or manipulation, or reorientation, or addition of non-solid	Using motion along or about the vertical axis	6	1.0	0.75	1.0	0.85	1.0	1.0	1.0	0.75	1.0	0.8	1.0	0.9	1.0	1.2	1.0	1.0	1.0	1.0							
		0	0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.5	2.1							
	Using motion along or about a non-vertical axis	7	1.5	0.75	1.5	0.85	1.5	1.0	1.5	0.75	1.5	0.8	1.5	0.9	1.5	1.2	1.5	1.0	1.5	2.0							
		0	0	0	0	0	0	0	1.5	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.5	2.1							
	Involving motion along or about more than one axis	8	1.5	1.4	1.5	1.6	1.5	1.8	1.5	1.4	1.5	1.5	1.5	1.7	1.5	2.0	1.5	1.8	1.5	3.2							
		0	0	0	0	0	0	0	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	1.5	2.1	4.5	2.1							

Figure 50: Classification system and data base for a single-station one arm robot assembly system

ROBOT ASSEMBLY DATA FOR A SINGLE-STATION TWO-ARM SYSTEM

AR	TP
AG	TG

TP - Relative affective basic operation time
 AR - Relative robot cost
 AG - Relative additional gripper or tool cost
 TG - Relative time penalty for gripper or tool change

Part added but not finally secured			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper										
			No holding down		Part requires temporary holding or clamping		No holding down		Part requires temporary holding or clamping								
			Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align							
			0	1	2	3	4	5	6	7							
Using motion along or about the vertical axis	0	1.0	0.55	1.0	0.6	1.5	0.85	1.5	0.9	1.0	0.6	1.0	0.6	1.5	0.85	1.5	0.9
		0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7
	1	1.5	0.55	1.5	0.6	1.5	0.85	1.5	0.9	1.5	0.6	1.5	0.6	1.5	0.85	1.5	0.9
		0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7
	2	1.5	1.05	1.5	1.1	1.5	1.3	1.5	1.4	1.5	1.05	1.5	1.1	1.5	1.3	1.5	1.4
		0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7

Part added and secured immediately			Force or torque levels within robot capability								Special workhead operation								
			Part can be gripped and inserted using standard gripper or gripper used for previous part				Part requires change to special gripper												
			Snap or push fit		Push and twist or other simple manipulation		Snap or push fit or simple manipulation		Screw fastening or nut running										
			Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align	Self-aligning	Not easy to align									
		0	1	2	3	4	5	6	7	8									
Using motion along or about the vertical axis	3	1.0	0.55	1.0	0.6	1.0	0.7	1.0	0.75	1.0	0.6	1.0	0.65	1.0	0.7	1.0	0.8	1.0	1.15
		0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.0	0.7
	4	1.5	0.55	1.5	0.6	1.5	0.7	1.5	0.75	1.5	0.6	1.5	0.65	1.5	0.7	1.5	0.8	1.5	1.15
		0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.0	0.7
	5	1.5	1.05	1.5	1.1	1.5	1.16	1.5	1.2	1.5	1.05	1.5	1.1					1.5	1.6
		0	0	0	0	0	0	0	0	1.5	0.7	1.5	0.7					4.0	0.7

Separate securing operation or manipulation, or reorientation, or addition of non-solid			Operation can be carried out using standard gripper or gripper used for previous operation			Operation requires change to special gripper or tool					Special workhead operation								
			Snap or push fit	Push and twist or simple manipulation	Reorient or unload assembly	Snap or push fit	Screw or nut tighten	Solder	Apply liquid or adhesive	Reorient or unload assembly									
			0	1	2	3	4	5	6	7									
			0	1	2	3	4	5	6	7									
Using motion along or about the vertical axis	6	1.0	0.45	1.0	0.5	1.0	0.6	1.0	0.45	1.0	0.5	1.0	0.55	1.0	0.7	1.0	0.6	1.0	0.15
		0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.0	0.7
	7	1.5	0.45	1.5	0.85	1.5	0.6	1.5	0.45	1.5	0.5	1.5	0.55	1.5	0.7	1.5	0.6	1.5	1.16
		0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.5	0.7
	8	1.5	0.8	1.5	0.9	1.5	1.05	1.5	0.8	1.5	0.85	1.5	1.0	1.5	1.15	1.5	1.05	1.5	1.8
		0	0	0	0	0	0	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	1.5	0.7	4.5	0.7

Figure 51: Classification system and data base for a single-station two arm robot assembly system

ROBOT ASSEMBLY DATA FOR A MULTI-STATION SYSTEM

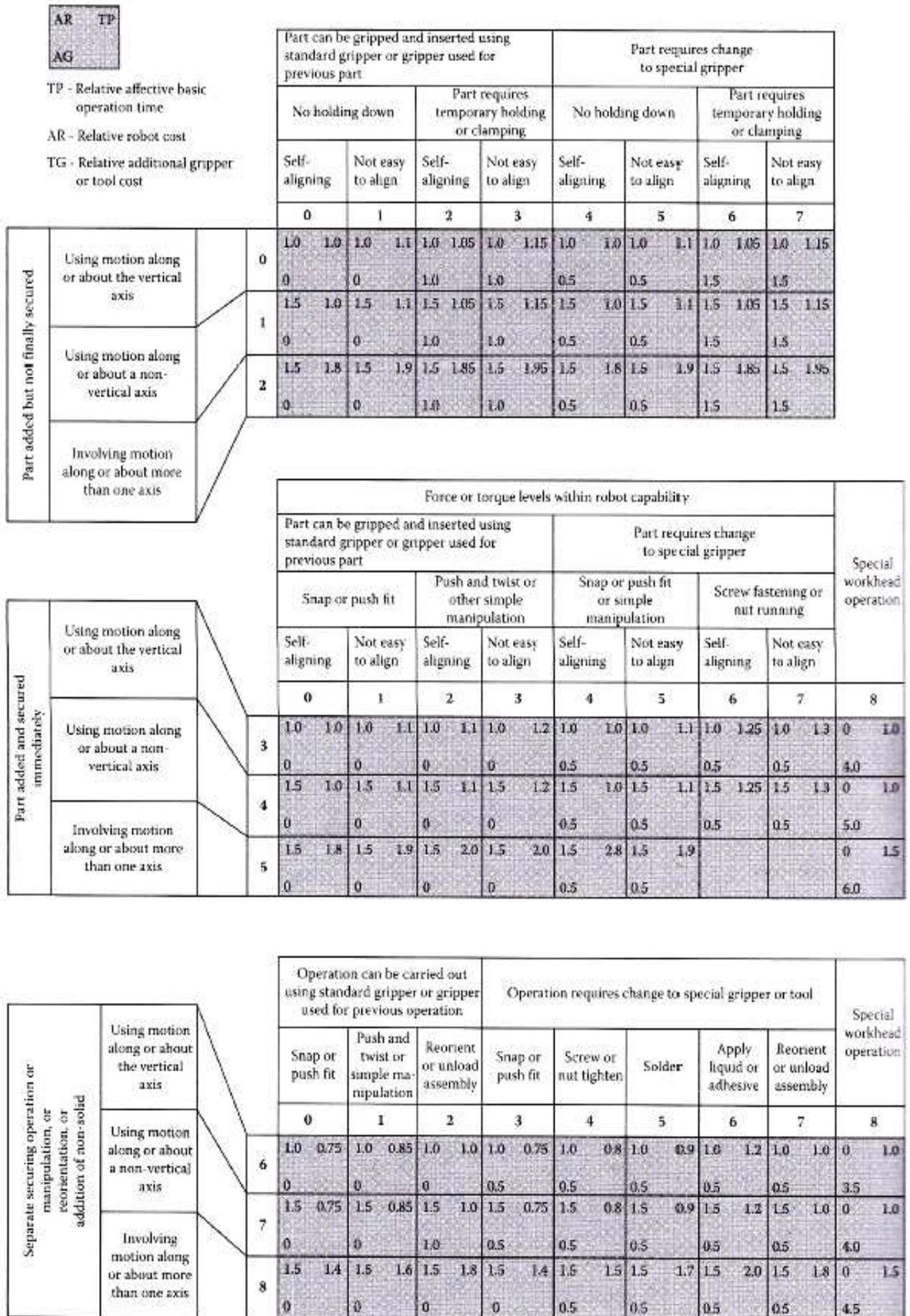


Figure 52: Classification system and data base for a multi-station system

METHODS-TIME DATA								
TABLE I - REACH								
Case	Description	DISTANCE MOVED INCHES	LEVELED TIME TMU'S					
			A STD.	A HAND IN MOT.	WITH A OR B	B HAND IN MOT.	C OR D	E
A	<i>Reach to object in fixed location or to object in other hand or on which other hand rests</i>	1			2.1		3.6	
		2			4.3		5.9	
		3			5.9		7.3	
		4	6.1	4.9	7.1	4.3	8.4	6.8
B	<i>Reach to single object in location which may vary slightly from cycle to cycle</i>	5	6.5	5.3	7.8	5.0	9.4	7.4
		6	7.0	5.7	8.6	5.7	10.1	8.0
		7	7.4	6.1	9.3	6.5	10.8	8.7
		8	7.9	6.5	10.1	7.2	11.5	9.3
		9	8.3	6.9	10.8	7.9	12.2	9.9
C	<i>Reach to object in group</i>	10	8.7	7.3	11.5	8.6	12.9	10.5
		12	9.6	8.1	12.9	10.1	14.2	11.8
		14	10.5	8.9	14.4	11.5	15.6	13.0
		16	11.4	9.7	15.8	12.9	17.0	14.2
D	<i>Reach to very small object or where accurate grasp is required</i>	18	12.3	10.5	17.2	14.4	18.4	15.5
		20	13.1	11.3	18.6		19.8	16.7
		22	14.0	12.1	20.1		21.2	18.0
		24	14.9	12.9	21.5		22.5	19.2
E	<i>Reach to indefinite location to get hand in position for body balance or next motion or out of way</i>	26	15.8	13.7	22.9		23.9	20.4
		28	16.7	14.5	24.4		26.3	21.7
		30	17.5	15.3	25.8		26.7	22.9

TABLE II - MOVE								
Case	Description	DISTANCE MOVED INCHES	LEVELED TIME TMU'S				MULTIPLYING FACTOR	
			A	B OR C	C	D B HAND IN MOT.	WEIGHT	FACTOR
A	<i>Move object against stop</i>	1	1.7	1.7	1.7		Up to 5	100
		2	3.6	4.2	4.2			
		3	4.9	5.7	5.7			
		4	6.1	6.9	7.3	4.3		
B	<i>Move object to approximate location</i>	5	7.3	8.0	8.7	5.0	15	105
		6	8.1	8.9	9.7	5.7	20	1.08
		7	8.9	9.7	10.8	6.5		
		8	9.7	10.6	11.8	7.2		
9	10.5	11.5	12.7	7.9				
C	<i>Move object to exact location</i>	10	11.3	12.2	13.5	8.6	25	1.11
		12	12.9	13.4	15.2	10.0		
		14	14.4	14.6	16.9	11.4		
		16	16.0	15.8	18.7	12.8		
D	<i>Toss object aside</i>	18	17.6	17.0	20.4	14.2	35	1.16
		20	19.2	18.2	22.1	15.6		
		22	20.8	19.4	23.8	17.0		
		24	22.4	20.6	25.5	18.4		
E	<i>Move object to indefinite location</i>	26	24.0	21.8			45	1.22
		28	25.5	23.1				
		30	27.1	24.3				

TABLE III - TURN					
DEG. TURNED	LEVELED TMU'S	DEG. TURNED	LEVELED TMU'S	Small	Med-
30°	2.8	120°	6.8	No load or parts up to 2-lbs Use table value	Turn is a special case of Reach or Move
45°	3.5	135°	7.4	Loads from 2.1 to 10lb	It is accomplished by a turning or torsional motion during which
60°	4.1	150°	8.1	1.57x table value	the hand and wrist turn When turn
75°	4.8	165°	8.7	Loads from 10.1 to 35lbs	is combined with a normal Reach
90°	5.4	180°	9.4	3x table value	or Move, determine time for Turn and
105°	6.1			Apply pressure 16.2 TMU'S	Reach or Move from the tables and
					use larger value

Figure 53: Methods-time data

METHODS – TIME DATA							
TABLE IV – GRASP							
Case	Description	LEVELED TIME T.M.U'S					
1a	<i>Pick up Grasp-Small, medium, or large object by itself-easily grasped</i>	1.7					
1b	<i>Very small object or tool handle lying close against flat surface</i>	3.5					
1c	<i>Interference with grasp on bottom and one side of object</i>	8.7					
2	<i>Regrasp</i>	5.6					
3	<i>Transfer Grasp</i>	5.6					
4	<i>Object jumbled with other objects so that Search and Select occur</i>	8.7					
5	<i>Contact, Sliding or Hook Grasp</i>	0					
TABLE V – POSITION							
		EASY TO HANDLE			DIFFICULT TO HANDLE		
CLASS OF FIT		SYMM	SEMI-SYMM	NON SYMM	SYMM	SEMI SYMM	NON SYMM
1 <i>Loose-No pressure required</i>		5.6	6.6		9.0	13.7	16.3
2 <i>Close-Light pressure required</i>			14.1	21.9	19.6	25.5	27.2
3 <i>Exact-Heavy pressure required</i>		39.4	43.9	53.1			
SYMMETRICAL <i>Object can be positioned in an infinite number of ways about the axis which coincides with the direction of travel</i>		SEMI-SYMMETRICAL <i>Object can be positioned in several ways about the axis which coincides with the direction of travel</i>		NON-SYMMETRICAL <i>Object can be positioned in only one way about the axis which coincides with the direction of travel</i>			
* <i>Distance moved to engage-1" or less</i>							
TABLE VI – DISENGAGE							
Class of Fit				EASY TO HANDLE	DIFFICULT TO HANDLE		
1 <i>Loose-very slight effort-Blends with subsequent move</i>				4.0	5.7		
2 <i>Close-Normal effort-Slight recoil</i>				7.5	11.8		
3 <i>Tight-Considerable effort-Hand recoils markedly</i>				22.9	34.7		
TABLE VII – RELEASE							
Case	Description	LEVELED TIME T.M.U'S					
1	<i>Normal Release performed by opening fingers as independent motion</i>	1.7					
2	<i>Contact Release</i>	0					

Figure 54: Methods-time data (continued)

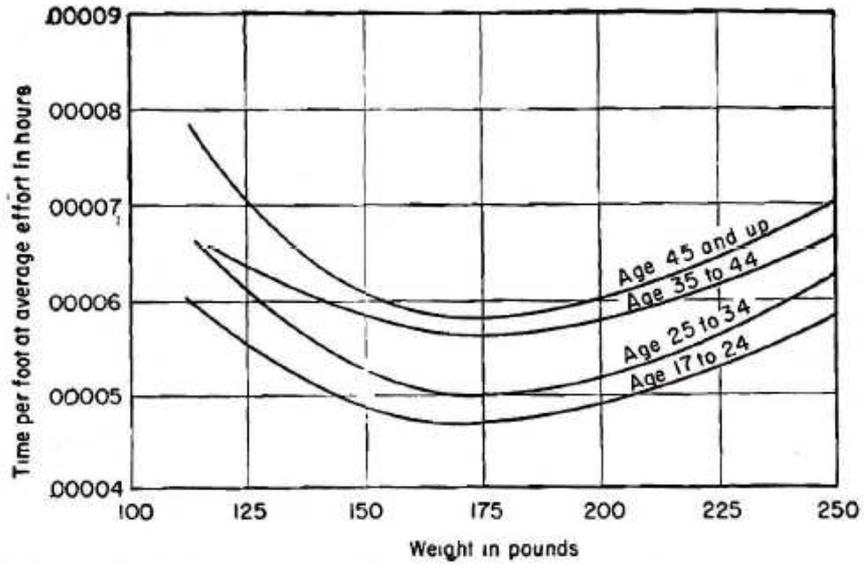


Figure 55: Effect of age and weight upon walking time per foot at average effort level